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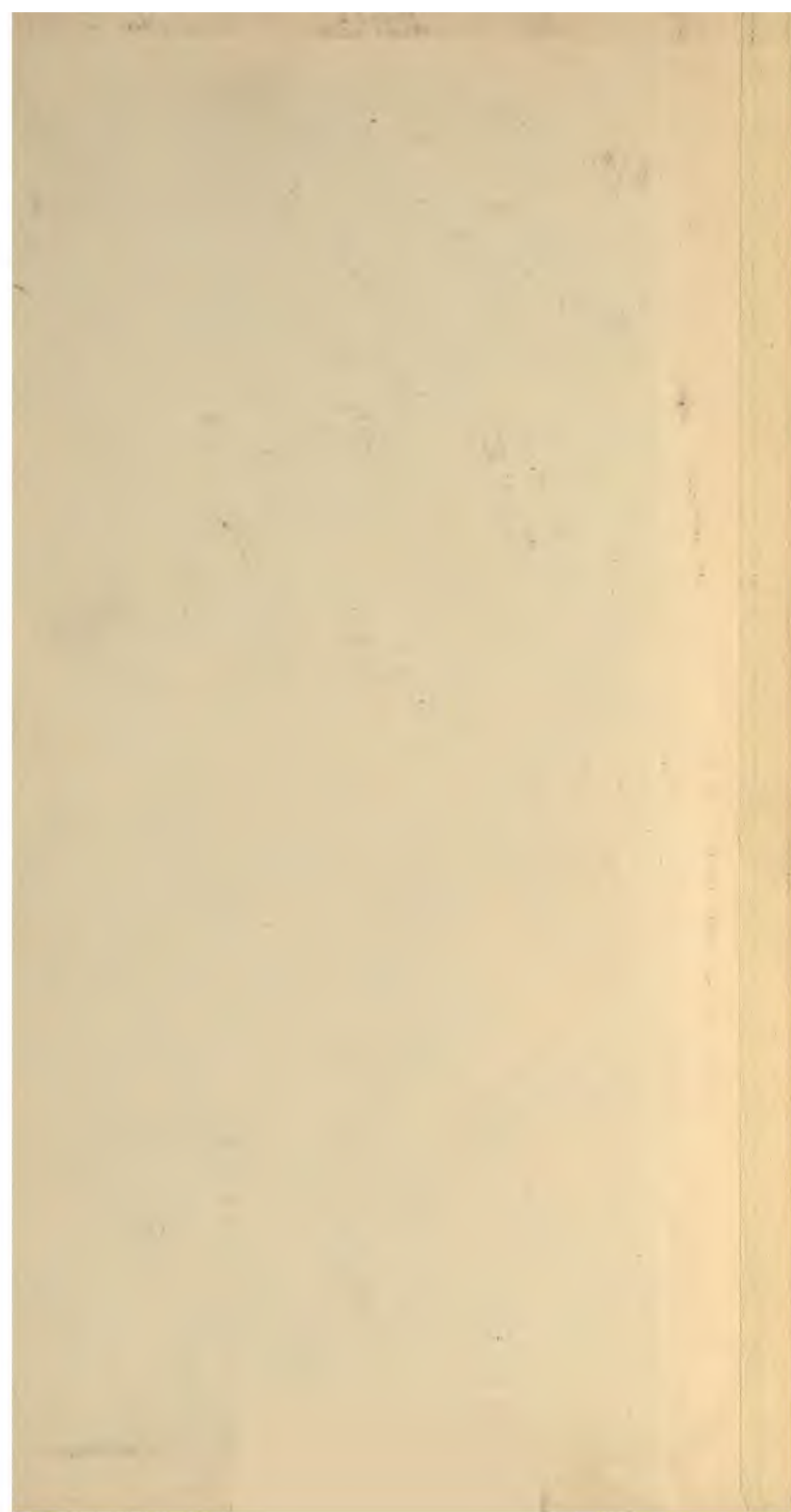
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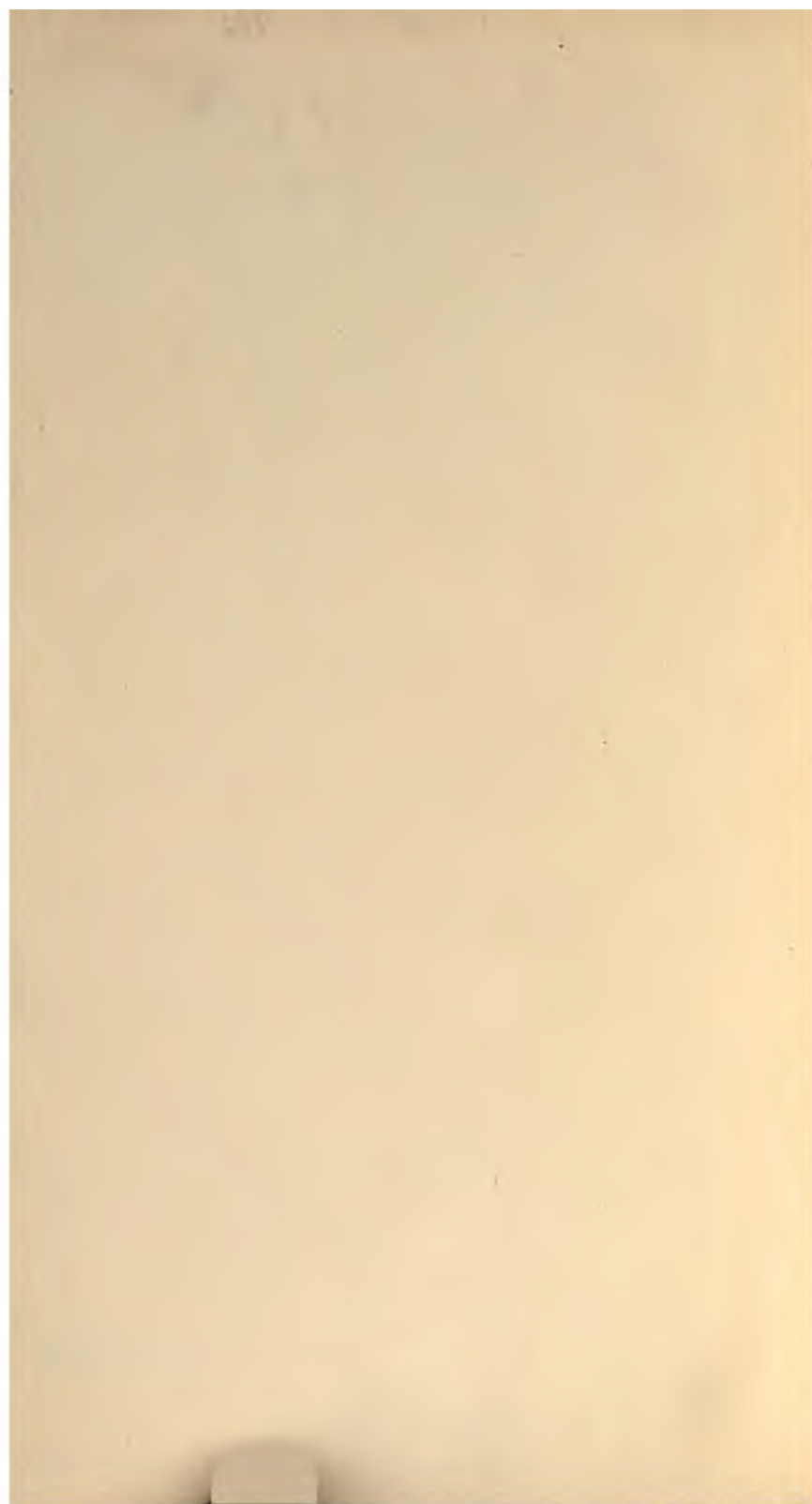


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# DESIGN OF DYNAMOS



# DESIGN OF DYNAMOS



# DESIGN OF DYNAMOS

BY

SILVANUS P. THOMPSON

D.Sc., F.R.S.

SECOND PRINTING



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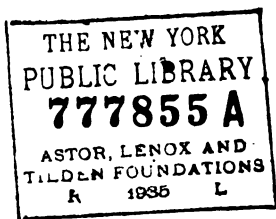
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## PREFACE.

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THESE notes on Dynamo Design are not intended to supersede the more complete handbooks on the special branch of electrical engineering of which this is only a part. In the forthcoming new (seventh) edition of the Author's *Dynamo-Electric Machinery* many other examples of design will be found. The present short work, intended primarily for the Author's own students, is purposely confined to continuous-current generators. As it will be used by engineers, chiefly in Great Britain, in her Colonies, and in the United States, the calculations and data have been expressed in inch measures. But the Author has adopted throughout the decimal subdivision of the inch; small lengths being given in mils, and small areas of cross-section in square mils, or, sometimes also, in circular mils, to suit American practice.

In the section on Armature Winding Schemes special attention is given to series-parallel windings, and to the doctrine of the "equivalent ring."

The Author's grateful acknowledgments are hereby given to various manufacturing firms and engineers who have supplied him from time to time with drawings and information that is made use of in this work, and in particular he is indebted to

the Oerlikon Machine Works, Messrs. Ernest Scott and Mountain, the Allgemeine Elektrizitäts-Gesellschaft, Messrs. Brown, Boveri & Co., the General Electric Co. of Schenectady, Messrs. Kolben & Co., the English Electric Manufacturing Co., the Electric Construction Co., the International Electrical Engineering Co., to La Compagnie de l'Industrie Électrique, of Geneva, to the British Thomson-Houston Co., to Mr. H. F. Parshall, and last, but not least, to Mr. A. C. Eborall.

He also acknowledges the substantial help rendered by his assistants, Mr. F. I. Hiss and Mr. E. W. Short, in calculation and tabulation, and in the preparation of cuts.

It is impossible to conclude these acknowledgments without a reference to the sudden and premature decease, while this work is passing through the press, of Professor Sidney H. Short, whose name occurs several times in its pages. The strong simplicity which characterized the machinery of his design was a reflex of the personal qualities which endeared him to many friends in the circle of electrical engineers on both sides of the Atlantic.

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*November, 1902.*

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# DESIGN OF DYNAMOS.

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## CHAPTER I.

### DYNAMO DESIGN AS AN ART.

DYNAMO DESIGN is an art not to be acquired without practice and experience; and like other branches of engineering design it reposes upon certain fundamental scientific principles. These can be laid down definitely, and taught with precision. But in the application of them in design to meet the varied needs of an ever expanding industry there is wide scope for choice and for individual preference. Time and experience have indeed taught the general lines along which dynamo design must proceed. But no one yet ever designed a successful dynamo by mere rules. A grasp of principles, electrical and mechanical; a knowledge of machinery and its construction; an acquaintance with the successful forms that exist; and a perception of the reasons why they are successful;—these and many other things are requisite in the designer who is to produce machines that will hold their own in the competition of to-day.

In his treatise on *Dynamo-Electric Machines* the author has treated the subject broadly, and with some reference not only to the historical evolution of the various types of machine, but also to the abstract theory which must be acquired if a thorough grasp of the subject is to be attained. But there are many engineers who have followed some course of instruction in the theoretical part of the sciences of magnetism and electricity, who yet have no knowledge of the way in

which that theory is applied in dynamo design. The immediate end and aim, therefore, of the present book is to give to such a working insight into the procedure of dynamo design as carried out in recent years for the construction of continuous current dynamos of modern type. Considerations of space, and the desire not to enter too far upon the topics treated of in the author's other works, *Dynamo-Electric Machinery*, *Polyphase Electric Currents*, *The Electromagnet* and *Elementary Lessons in Electricity and Magnetism*, have determined him to confine the present publication strictly to the design of *Continuous Current Generators*, and of these to treat only of the principal kind, leaving aside small machines, and special types such as arc-lighting machines. These are treated of in his larger work on *Dynamo-Electric Machinery*. To that work those readers are referred who, for want of previous general acquaintance with the subject, find the considerations laid down in the following chapters to assume points that are not familiar to them. The Author assumes, indeed, that his reader has some acquaintance with such matters as elementary magnetism and the magnetic properties of iron, permeability and hysteresis. He also assumes a general knowledge of electric conduction and insulation, and of the elements of electrical measurement.

The present work does not go into the theories of armature winding, nor into the practical modes of carrying it out in the shop. For these also he refers the reader to his larger treatise.

After all, however fundamental the necessity of scientific principles, sound theories, and rules derived from the experience and practice of others, dynamo design remains an art. It needs the eye to see, as well as the mind to understand.

## CHAPTER II.

## MAGNETIC DATA AND CALCULATIONS.

ALL dynamo design is based upon a knowledge of the magnetic properties of iron and steel. During the past twenty years thousands of brands of various qualities have been subjected to test as to their magnetic properties by scientific authorities, and there exists an extensive literature on the subject. The principal thing to know is the appropriate density of the magnetic flux, and the amount of excitation required to produce it, in any given specimen. In this book the letter **N** is used to denote *the magnetic flux*, that is to say, the total number of magnetic lines, carried by any iron core. If the area of section of this core is denoted by the letter A, the density of the magnetic flux will be equal to  $N \div A$ . When the sectional area is given in square inches the letter used to denote the *flux-density* (i.e. the number of magnetic lines per square inch) is **B**. In cases where the area is given in square centimetres, the letter used for the flux-density will be **ℬ**. The magnetizing forces required to excite any required flux-density in the magnetic circuit of a dynamo are obtained by causing an electric current to circulate around the iron core. It is found that the magnetizing force thus produced is proportional both to the amount of current (i.e. the number of *amperes*) so flowing, and to the number of times it circulates around the core (i.e. the number of *turns* in the magnetizing coil). In other words, the magnetizing force is proportional to the number of *ampere-turns*. For brevity we sometimes describe the total number of ampere-turns of

circulation of current around a core as "the *excitation*." It goes without saying that the higher the flux-density required, and the greater the length of the iron through which the magnetic flux is to be driven, the greater is the amount of excitation needed. To drive a magnetic flux through air requires a much greater amount of excitation than is required for an equal flux-density through an equal length of iron. The coefficients used in calculating air-gaps are mentioned on p. 28. In treatises on theoretical magnetism it is usual to describe magnetizing forces in terms of a theoretical unit (derived from the Centimetre-gramme-second system), which is such that if applied to an air-core one centimetre in length it would produce a flux-density of one line per square centimetre. The usual symbol for denoting the theoretical value of magnetizing forces in terms of this unit is  $\mathcal{H}$ . For example, suppose it was stated that the magnetizing forces were such in some case that  $\mathcal{H} = 50$ , this would mean that they were so strong that if applied to a layer of air 1 centimetre thick they would produce in the air a flux-density of 50 lines per square centimetre. If applied to an equal length of iron, the resulting flux-density  $\mathcal{B}$  would be immensely greater, since iron is much more permeable magnetically. The ratio of  $\mathcal{B}$  to  $\mathcal{H}$  in any material is called its *permeability*. The magnetic properties of iron, and the variations of its permeability, may be described in various ways by statistical tables, derived from experiments. But for practical purposes it is far more convenient to exhibit them by means of *magnetization curves*, that is, curves connecting the amount of flux-density produced in the material with the magnetizing force necessary to produce it. Moreover, as the ratio of the former to the latter is a measure of the permeability of the material with which we have to deal, and we might use this ratio to estimate the amount of magnetism that would be produced in a given material by the action of a definite magnetizing force or vice versa. In commercial work, however, it is found more convenient to dispense altogether with the permeability in magnetic calculations, and to work directly with the ampere-turns required per unit length of material in order to produce a

definite flux-density in it. For instance, we know<sup>1</sup> that the magnetizing force  $\mathcal{H}$  is related to the ampere-turns per centimetre of length by the equation :

$$\mathcal{H} = \frac{4 \pi C S}{10 l};$$

where  $C$  is the current in amperes,  $S$  the number of turns and  $l$  the length in centimetres. Transposing, we find that the number of *ampere-turns per centimetre of length* will have the value

$$\frac{C S}{l} = \frac{10}{4 \pi} \mathcal{H}.$$

And, as 1 inch = 2.54 centimetres, we shall have for the number of *ampere-turns per inch* length of material, the value

$$\frac{C S}{l''} = \frac{2.54 \times 10}{4 \pi} \mathcal{H} = 2.02 \mathcal{H}.$$

Hence, if we have already got, for any specimen of iron, the curve connecting  $\mathfrak{B}$  and  $\mathcal{H}$ , we can at once change the  $\mathcal{H}$  values for the more convenient *ampere-turns per inch* by changing the scale of the abscissæ; the point, for example, marked 50 on the  $\mathcal{H}$  axis will now read 101 on the scale of ampere-turns per inch.

Such a set of curves, connecting the flux-density in lines per square inch with the ampere-turns required per inch of magnetic path, in different materials is given in Plate I. The curve marked I. is for armature sheet, and represents this material as supplied by Messrs. Shaw, of Middlesboro'. Curve II. represents the cast steel for dynamo purposes made by Messrs. Edgar Allen, of Sheffield. Curves III., IV. and V. are for good wrought iron, malleable cast iron and good cast iron, respectively. In the drawing office each dynamo designer

<sup>1</sup> Readers who desire further information about magnetic units and their measurement should refer to the Author's *Elementary Lessons in Electricity and Magnetism*, or to his treatise on *The Electromagnet*. In the latter will also be found an account of the various methods of measuring the magnetic qualities of iron.

ought to provide himself with similar curves for the particular brands of iron and steel which he uses. All the good makers of iron and steel for dynamo purposes will furnish curves for the materials which they produce. The additional curves given in Fig. 1 relate to wrought iron when worked at very high flux-densities; one is due to Mr. Parshall, the other relates to Messrs. Sankey's special quality of armature stampings. Such curves find their principal application in calculating the ampere-turns required for the teeth of slotted armatures, which are frequently worked at very high flux-densities; but they must be used with caution, on account of the limited amount of knowledge at present available on this subject. Mr. H. S. Meyer gives measurements<sup>1</sup> on a sample of still higher quality.

Barrett<sup>2</sup> has recently found that a particular steel containing  $2\frac{1}{4}$  per cent. of aluminium, made by Hadfield, of Sheffield, has a higher permeability than any known brand of wrought iron.

Looking at the curves of Plate I., one sees that if one wishes to know, for example, how much magnetizing force is required to produce a flux-density of, say,  $B = 100,000$  lines per square inch, in wrought iron, one follows out the curve of wrought iron up to the level of 100,000, and then dropping perpendicularly on to the horizontal scale one observes that it will require 73 ampere-turns per inch length of the iron.

*Example.*—Find the number of ampere-turns of excitation necessary to drive a flux of 12,000,000 lines through a cast-iron yoke, the cross-section of which is 300 square inches, and the length 17 inches. Since 300 square inches carry 12,000,000 lines, the flux-density  $B$  will be 40,000 lines per square inch. Reference to the curve for cast iron on Plate I will show that this will require 77 ampere-turns per inch; and as the iron is 17 inches long the answer is  $17 \times 77 = 1309$  ampere-turns.

Further examination will show that though for flux-densities below 85,000, *mild cast steel* is less magnetizable than wrought iron, yet at higher flux-densities the mild steel is

<sup>1</sup> *Elektrot. Zeitschrift*, xxxv. 769, September 12, 1901.

<sup>2</sup> See *Journ. Inst. Elec. Engineers*, xxxi. 709, 1902.

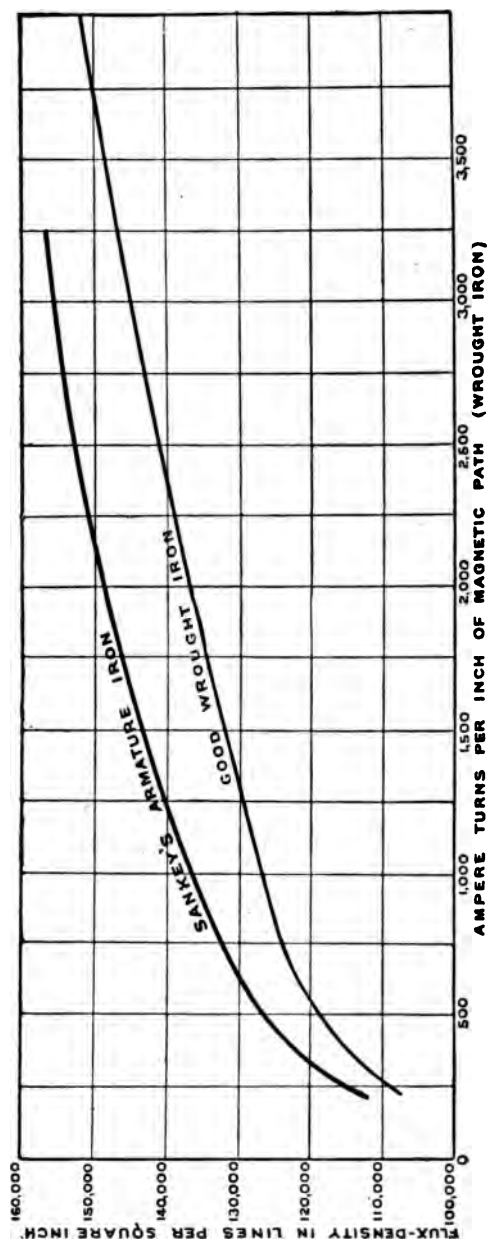


FIG. 1.—MAGNETIZATION-CURVE AT VERY HIGH DENSITIES.

equally good or even better. Being cheaper, it has come very largely into use for dynamo magnets and pole-cores. Though called "mild steel," it is in reality very nearly pure iron, as it contains only about 0·2 per cent. of carbon, and is incapable of taking a temper.

For an account of the various methods of measuring<sup>1</sup> the magnetic qualities of iron, and for detailed information as to the newest kinds of iron and magnet steel, see the author's treatise on *The Electromagnet*.

Sheet iron often shows very different qualities in different parts of the same sheet. According to Röhr,<sup>2</sup> parts near the edges of the sheet are often better annealed than parts from the middle. Repeated annealing tends to make any sample more homogeneous magnetically. The most homogeneous magnetic material hitherto produced is annealed cast steel.

*Heat wasted in Cycles of Magnetization.*—It has long been known that when iron is subjected to rapidly recurring magnetization and demagnetization, or to an alternating magnetization, it becomes hot. This heat so wasted in the iron is due to two causes, (1) hysteresis, (2) eddy-currents.

Hysteresis is a species of magnetic fatigue which wastes energy at every reversal of the magnetization, particularly in all hard kinds of iron and steel. To minimize this source of loss the cores of armatures must be made of material which has as low a hysteresis as possible.

Eddy-currents are currents induced in the substance of the

<sup>1</sup> Consult also the following works:—

Ewing J. A., various papers in the *Philosophical Transactions* of the Royal Society in the years 1885 to 1894. A full résumé is given in his book *Magnetic Induction in Iron and other Metals*. London, 1894.

Hopkinson, Dr. J., papers in the *Philosophical Transactions* of the Royal Society, 1885 to 1895. Those of chief importance are reprinted in his *Original Papers* (1901), vol. i.

Du Bois, H. J. G., *Magnetische Kreise, deren Theorie und Anwendungen*. Berlin, 1894.

Jackson, Dugald C., *Electromagnetism and the Construction of Dynamos* (Macmillan).

Parshall, H. F., *Electric Generators*, London, 1900; also *Proc. Inst. Civil Engineers*, cxxvi. May 19, 1896.

Schmidt, Dr. E., *Die Magnetische Untersuchung des Eisens*. Halle, 1900.

<sup>2</sup> *Elektrot. Zeitschr.*, xix. 712, 1898.

iron core itself by the magnetic changes. They can be reduced indefinitely by laminating the cores, which are built up of thin sheets of iron or of a special soft steel; the usual thickness being from 25 to 40 mils thick, though in some cases core-sheets as thin as 15 mils (= about 0.6 millimetre) are employed.

*Calculation of Heat-Waste in Iron Cores.*—The energy lost per cycle depends not only upon the nature of the material but also upon the degree to which the magnetization is carried in each cycle—in fact upon the *amplitude* of the cycle. The loss of energy per cycle is more than proportionally great; doubling  $\mathfrak{B}$  more than doubles the energy loss per cycle.

Mr. C. P. Steinmetz<sup>1</sup> has given the following law connecting the hysteresis loss  $h$  in ergs per cubic centimetre of iron per cycle and the flux-density  $\mathfrak{B}$ . He finds that

$$h = \eta \mathfrak{B}^{1.6}$$

where  $\eta$  is a constant, called the hysteretic constant, depending upon the kind of iron. This law is true for cycles performed either slowly, or as rapidly as 200 per second. The following table gives the hysteretic constant  $\eta$  for different materials<sup>2</sup> when ordinary frequencies are employed.

From experiments with actual transformer plates, at  $n$  cycles per second, the hysteretic loss, in watts per cubic inch of iron, was found to be

$$W_h = 0.83 \times \eta \times n \times \mathfrak{B}^{1.6} \times 10^{-7}.$$

In Fig. 2 there have been plotted the hysteresis losses in watts per pound of iron, at a frequency of 30 cycles per second,

<sup>1</sup> *Amer. Inst. Elec. Engineers*, Jan. 19, 1892; *Electrician*, Feb. 12, 19 and 26, 1892. The exponent is not always exactly 1.6: it varies between 1.5 and 1.9.

<sup>2</sup> For particulars of Ewing's Magnetic Tester for measuring Hysteresis in sheet iron, see *Inst. Elec. Engineers*, April 25, 1895; also *Electricians*, xxxiv. 786. To reduce these values from ergs per cubic centimetre per cycle to the more ordinary value in watts per pound of iron at 100 cycles per second, multiply by the factor 0.000589. Barrett finds the values for Swedish charcoal iron, for Sankey's "Lohys" iron, and for aluminium-iron to be respectively 0.38, 0.32 and 0.23 watts per pound, with a maximum flux-density of 4000 lines per square centimetre.

for different values of the flux-density (in British measure). The iron is here taken to be of an ordinary good quality.

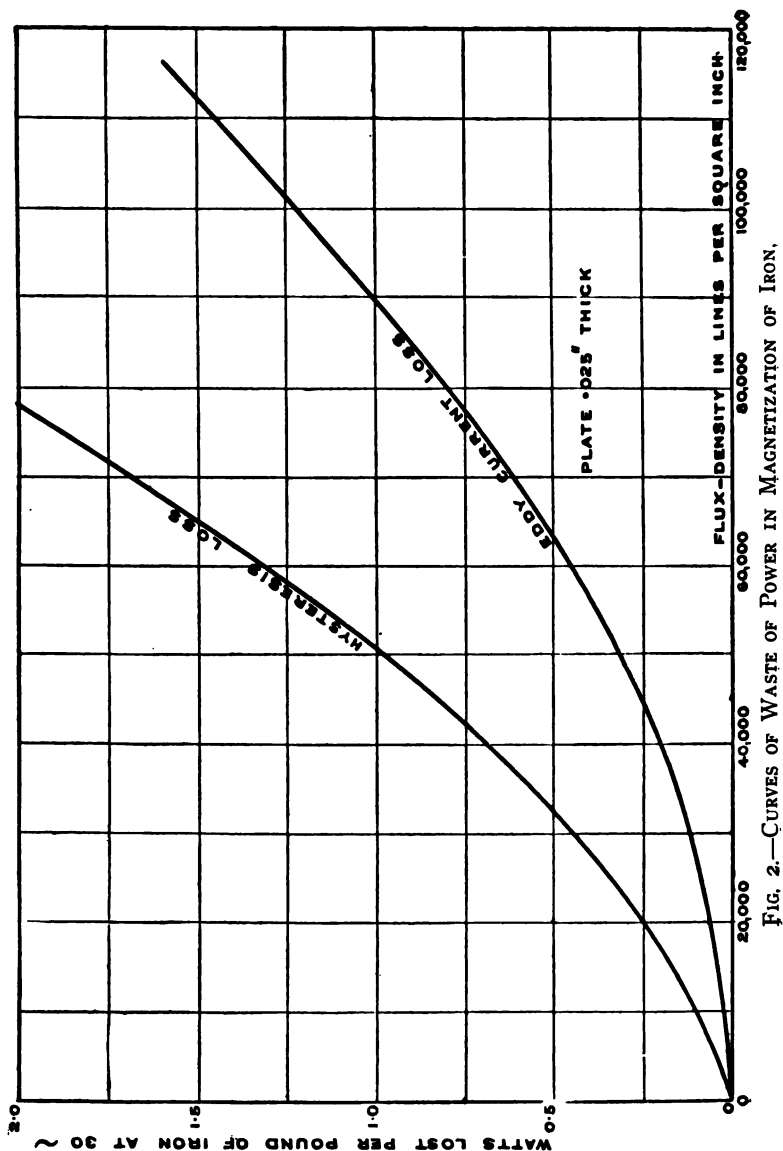


FIG. 2.—CURVES OF WASTE OF POWER IN MAGNETIZATION OF IRON.

TABLE I.—HYSTERETIC CONSTANTS FOR DIFFERENT MATERIALS.

Material.	Hysteretic constant $\eta$ .	Material.	Hysteretic constant $\eta$ .
Very soft iron wire . .	'002	Soft annealed cast iron .	'008
Very thin soft sheet iron .	'0024	Soft machine steel . . .	'0094
Thin good sheet iron . .	'003	Cast steel . . . . .	'012
Thick sheet iron . . .	'0033	Cast iron . . . . .	'016
Most ordinary sheet iron .	'004	Hardened cast steel . .	'025
Sankey's Lohys iron . .	'0012	Barrett's aluminium-iron	'00068

Similarly, Fig. 3 gives in the form of a graph the losses, by hysteresis, in watts *per cubic inch* of *laminated iron*, such as is used in armature cores; the curve in this case being plótted for *one* cycle per second, the corresponding flux-densities being given per square inch.

*Example.*—Find the power wasted by hysteresis in the core-body of the 8-pole dynamo, page 146, assuming  $B = 65,000$ , the total volume of the iron being 16320 cub. inches, and the frequency of the reversals 30 cycles per second.

TABLE II.—WASTE OF POWER BY HYSTERESIS.

$\oint B \, dl$ Per square centimetre.	$B$ Per square inch.	Watts wasted per cubic inch at 1 cycle per second.	Watts wasted per cubic foot at 10 cycles per second.	Watts wasted per cubic foot at 100 cycles per second.
4,000	25,800	0'0023	40	400
5,000	32,250	0'0033	57'5	575
6,000	38,700	0'0043	75	750
7,000	45,150	0'0053	92'5	925
8,000	51,600	0'0064	111	1110
10,000	64,500	0'0090	156	1560
12,000	77,400	0'0119	206	2060
14,000	90,300	0'0151	262	2620
16,000	103,200	0'0186	324	3240
17,000	109,650	0'0228	394	3940
18,000	116,100	0'0282	487	4870

Table II. gives the number of watts wasted by hysteresis in well-laminated soft wrought iron when subjected to a succession of rapid cycles of magnetization.

To facilitate calculations, Table III. gives the number of watts wasted per cubic inch per cycle for three different values of the hysteretic constant.

TABLE III.

Lines per square inch.	Watts wasted per cubic inch of iron per cycle per second.		
B	$\eta = 0.002.$	$\eta = 0.003.$	$\eta = 0.004$
40,000	0.003829	0.005767	0.007658
50,000	0.005478	0.008280	0.010956
60,000	0.007320	0.011080	0.014640
70,000	0.009345	0.014090	0.018690
80,000	0.011586	0.017455	0.023172
90,000	0.013993	0.021082	0.027986
100,000	0.016666	0.025000	0.033333
110,000	0.019322	0.029100	0.038644
120,000	0.022094	0.033425	0.044188
130,000	0.025248	0.038025	0.050496
140,000	0.028386	0.042750	0.056772

These values are plotted in the curves of Fig. 3. For other frequencies the values must be multiplied *simply by the frequency*.

Besides the hysteretic loss in iron plates, there is also a loss due to *eddy-currents* in the iron. This loss varies as the square of the thickness of the iron, the square of the frequency, and the square of the flux-density. There has been obtained by calculation the formula

$$W_e = 40.64 \times t^2 B^2 n^2 \times 10^{-12},$$

$W_e$  being the loss in watts per cubic inch of core made up of the strip, and  $t$  being the thickness of the strip in inches. Thus

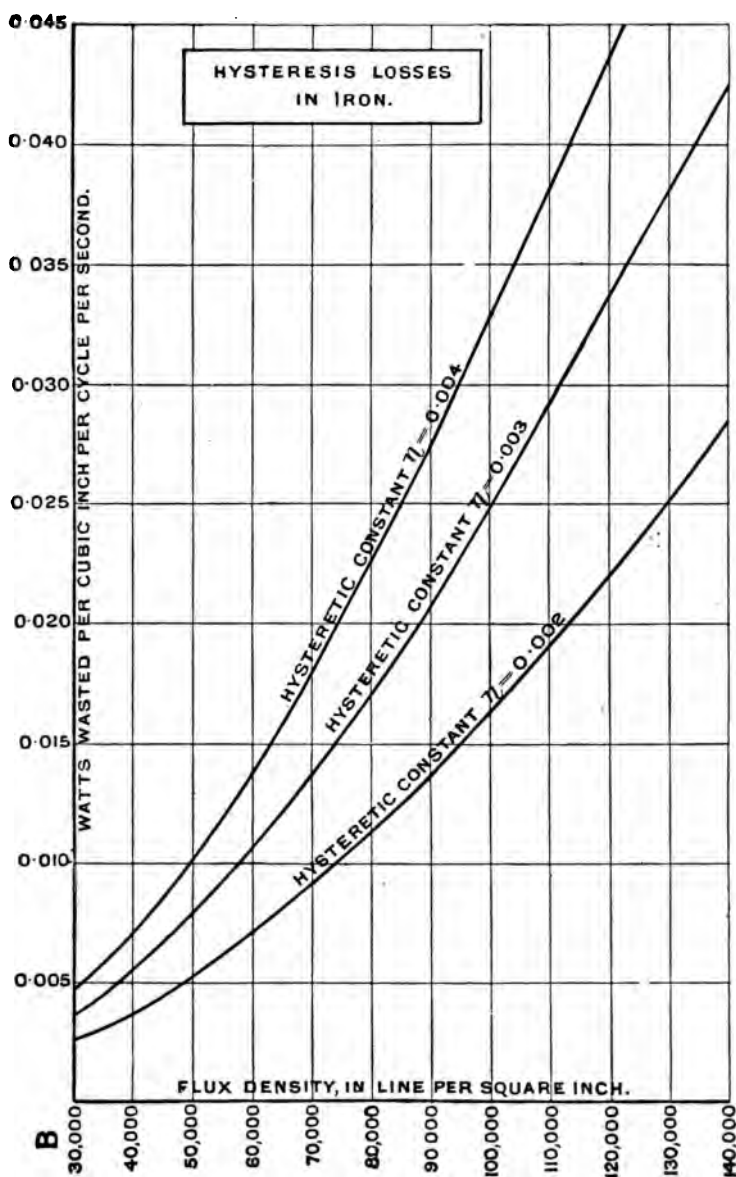


FIG. 3.—HYSTERESIS LOSSES IN WATTS PER CUBIC INCH.

we have the total loss in watts per cubic inch, due to both hysteresis and eddy-currents—

$$W = 0.83 \eta n B^{1.6} \times 10^{-7} + 40.64 t^2 B^2 n^2 \times 10^{-12}.$$

This has been found to agree very closely with practice.

In order to adapt the data to British measures, and to facilitate computation, Table IV. has been prepared, showing the values of the eddy-current losses in sheet iron of four different thicknesses, with a frequency of one cycle per second. The values for other frequencies will require to be multiplied by the *square of the frequency*.

TABLE IV.

B	Eddy-current loss in watts per cubic inch, at 1 cycle per sec.			
	<i>t</i> = 10 mils	<i>t</i> = 20 mils	<i>t</i> = 40 mils	<i>t</i> = 60 mils
40,000	0.000006	0.000026	0.000104	0.000234
50,000	0.000010	0.000040	0.000162	0.000366
60,000	0.000015	0.000058	0.000234	0.000527
70,000	0.000020	0.000079	0.000318	0.000717
80,000	0.000025	0.000104	0.000416	0.000935
90,000	0.000033	0.000132	0.000526	0.001185
100,000	0.000041	0.000162	0.000650	0.001463
110,000	0.000049	0.000196	0.000787	0.001770
120,000	0.000058	0.000234	0.000936	0.002107
130,000	0.000068	0.000275	0.001099	0.002490
140,000	0.000080	0.000318	0.001275	0.002867

These figures are graphically plotted for reference in Fig 4.

*Example.*—Find the number of watts wasted by eddy-currents in the armature core-body (not including teeth) of the 8-pole dynamo described on p. 146. Taking  $B = 65,000$  lines per square inch, the frequency 10 cycles per second, the thickness of the core-disks as 40 mils, and the number of nett cubic inches of iron as 16,320, we proceed as follows. Referring to the curves of Fig. 4 we pick out

the curve for 40-mil iron, and follow it up to opposite the value of 65,000, at which point we read off on the other scale the value 0.000275 as the number of watts per cubic inch at a frequency of 1 cycle per second. Then multiplying up by the square of the fre-

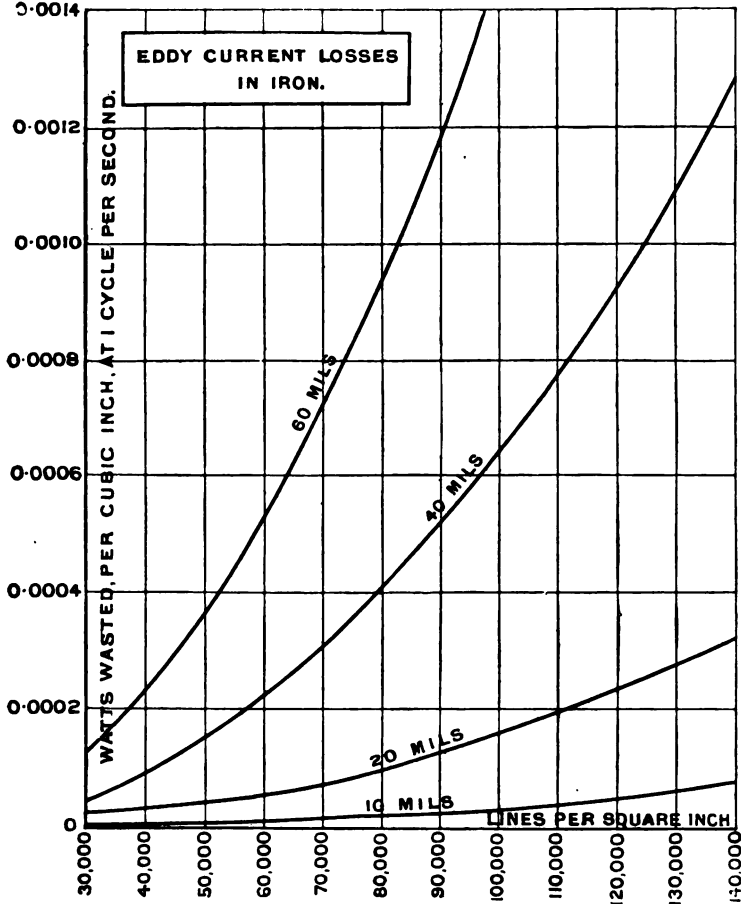


FIG. 4.—EDDY-CURRENT LOSSES IN SHEET IRON.

quency, and by the number of cubic inches, we find as the total eddy-current waste, 449 watts. Had we taken core-disks of half the thickness this waste would have been reduced to 112 watts.

Examples of calculation of the waste of power by eddy-

currents and hysteresis in the iron—usually called, for brevity, *the iron-losses*—in the armatures of continuous current dynamos will be found in Chapter VIII. pages 168 and 182.

Ewing has shown that vibration tends to destroy residual effects. There is also some evidence that with very rapid frequencies there is less work wasted per cycle than there would be in the same cycle performed slowly.

*Rotational Hysteresis.*—When an armature core is rotated in a strong magnetic field the magnetization of the iron is being continually carried through a cycle, but in a manner quite different from that in which it is carried when the magnetizing force is periodically reversed, as in the core of a transformer. Mordey has found<sup>1</sup> the losses by hysteresis to be somewhat smaller in the former case than in the latter. Baily<sup>2</sup> found the losses, for a rotating density lower than  $\mathfrak{B} = 15,000$ , to be slightly lower than is the case for alternating fields; but in stronger fields the rotational losses diminished after that point, and became nearly zero when  $\mathfrak{B} = 20,000$ . Dina<sup>3</sup> has, however, failed to confirm the latter result.

*Retardation of Magnetization.*—It has long been known that in solid cores of electromagnets the rise and fall of the magnetism is retarded by eddy-currents in the iron, the outside part of the iron becoming magnetized first when the current is turned on; whilst the magnetism of the inner parts grows up later as the eddy-currents in the outer part die away. There is thus a regular penetration or propagation of the magnetism from the outer to the inner parts of the core. When the magnetizing-current is cut off, the inner part is the last to lose its magnetism. In large dynamos many minutes may elapse before the magnetism attains its maximum. For this reason the author pronounced it useless to put a compound winding upon certain dynamos with large solid bipolar electro-magnets for use as electric railway generators. Hopkinson<sup>4</sup> showed that the retardation varies as the square of the linear dimensions.

<sup>1</sup> See also Ewing in *Electrician*, xxvii. 602, 1891.

<sup>2</sup> *Phil. Trans.*, clxxxvii. 715, 1896.

<sup>3</sup> *Elektrot. Zeitschrift*, xxxv. 43, 1902.

<sup>4</sup> *Journ. Inst. Elec. Engineers*, Feb. 1895, and *Phil. Trans.*, 1895.

*Magnetic Dampers.*—If a magnetic flux, whether in air or in iron, be surrounded by a closed conductor such as a copper ring or tube, or a copper wire coil the ends of which are united together to form a closed circuit, it is impossible either to increase or to diminish this magnetic flux without setting up induced currents in the surrounding conductor; and these induced currents always tend to oppose, and therefore to delay the change of the flux. Hence, it is possible to protect any magnet pole against sudden changes in its magnetism by the simple device of surrounding it with a solid coil or circuit of copper to act as a *magnetic damper*. For this end Brush, in 1878, surrounded the limbs of his field-magnets with a copper tube. In recent times Hutin and Leblanc have proposed a device called an *amortisseur* (i.e. a *damper*) to prevent distortions of the magnetic field under the poles. For similar reasons the Westinghouse Co. inserts copper dampers between the pole-tips of its alternators and converters. A copper ring round a pole may thus prevent rapid changes in the enclosed flux, but cannot prevent distortion within the enclosed space from one part of the pole-face to another. To prevent this, or lessen it, one or more copper bars must be inserted across the pole-face and short-circuited together by outer bands. As induced currents can be set up in solid iron or steel as well as in copper it follows that solid steel pole-shoes to some extent serve the same purpose as magnetic dampers, though less effectively than an *amortisseur*.

#### COEFFICIENT OF DISPERSION.

To produce a definite electromotive-force with a given number of conductors rotating at a given speed, a certain magnetic flux must be cut by them. The function of the field system of a dynamo is to provide this flux, which may be called the *useful flux* because it is the actual flux being cut by the conductors and producing the electromotive-force. Now look at Fig. 5, which shows a typical bipolar magnetic circuit. In addition to the useful flux in the air-gap, there is a stray flux from all parts of the field system, and both the useful and stray

fluxes have to be produced by the exciting ampere-turns wound on the magnet limbs.

If we call the total flux (per pole) produced by the exciting coils in the magnet core  $N_m$ , the useful flux which actually enters the armature  $N_a$ ; and the stray flux which is dispersed  $N_s$ ; then obviously

$$N_m = N_a + N_s.$$

The ratio of the stray flux to the useful flux is sometimes called the *dispersion*. The ratio of the total flux to the useful

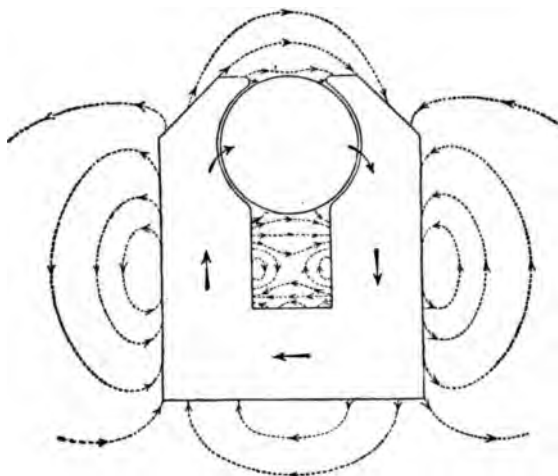


FIG. 5.—STRAY FIELD OF A BIPOLAR DYNAMO.

flux is called the *coefficient of dispersion*, or *coefficient of allowance for leakage*, or, less correctly, the *leakage coefficient*, and is denoted by the symbol  $\nu$ . Thus we have

$$\nu = \frac{N_m}{N_a}.$$

This coefficient of dispersion is therefore a number greater than unity. It varies between 1.15 and 1.7 in the usual types of machine.

*Example.*—In a certain 8-pole tramway generator the total flux per pole in the magnet core was 18,672,000 lines. Of these only 15,400,000

entered the armature, while 2,772,000 were dispersed. The coefficient of dispersion was therefore  $\nu = 1.18$ , the stray flux being 18 per cent. of the useful flux.

Although the stray field does not cause a waste of energy, yet it is objectionable in any class of machine on account of the extra material that must be put into the field system to make up for it—that is, more iron is necessary in the yoke and pole cores to carry the extra flux, and the length of each turn of the copper winding round them is increased. It becomes of importance, therefore, to design magnetic circuits to have a minimum amount of magnetic dispersion in order to save expense. The magnitude of the stray field depends chiefly upon (a) shape of the magnet limbs—thus circular cores will have less leakage than those of rectangular shape, on account of the smaller area of the side flanks; (b) upon the length of the air-gap, because the greater the reluctance of the latter the greater the tendency for the flux to take other alternative paths; and (c) upon the degree of saturation to which the field system is pushed, because the magnetic conductivity of the leakage paths in the air is constant while that of the iron cores decreases as the degree of saturation is raised. It is evident, therefore also, that not only will the coefficient of dispersion vary with different types of machine, but it cannot, as a rule be constant with a given machine but must vary with the excitation. Moreover, when a large current is being taken from the armature, the demagnetizing action of the armature due to the forward lead of the brushes, directly promotes dispersion, as it raises an opposing magnetomotive-force in the direct path of the magnetic lines, tending to blow them aside, as it were.

The most accurate way of finding the dispersion coefficient of a machine is by experiment. If in the case of a bipolar dynamo we wind around the armature a search coil with its plane at right angles to the magnetic flux, and connect it up to a ballistic galvanometer, we shall, upon making or breaking the exciting current, obtain a throw  $D_1$  proportional to the flux passing from pole to pole. If the search coil be wound upon the limbs just at the neck of an exciting coil, a second throw  $D_2$  may be obtained in the same way, and which will be propor-

tional to the total flux produced by the windings. Then we have

$$\nu = \frac{D_2}{D_1}$$

for the particular excitation used.

Before each reading, the current in the fields should be reversed several times in order to wipe out any residual magnetism. In order to allow for the effect of the armature current, a few accumulators in series with an adjustable resistance may be connected to the brushes, and an appropriate lead given to them the direction and amount of the current being such that the armature demagnetizes the field-magnets to the same extent as would be the case with the machine running on full load. The ratio of the maximum throw to the throw given by the armature search coil under these conditions will then approximately give the full-load dispersion coefficient. The principal objection to this method is the great strain it imposes upon the insulation of the magnet coils. As a general rule it cannot be employed with shunt windings, and for such machines a test-winding of fewer turns (and correspondingly larger section) must be wound on.

This method is due to the late Dr. J. Hopkinson, who found the dispersion coefficient of a bipolar dynamo of the "under" type to be 1.32.

Another method is by means of an alternate current. Wind on a search coil of  $S_2$  turns as before, and connect it to a voltmeter. Now send an alternating current (preferably of low frequency) of known electromotive-force  $E_1$  round the field coils, whose number of turns  $S_1$  is known. Let the voltmeter reading be  $E_2$ . Then

$$N_M \propto \frac{E_1}{S_1} \text{ and } N_a \propto \frac{E_2}{S_2}$$

Hence

$$\nu = \frac{E_1 \times S_2}{E_2 \times S_1}$$

The eddy-currents produced by the alternating flux in the

solid cores would not affect the results, but might be inconvenient if the current was left on too long.

The third way of determining the dispersion coefficient is by experiment upon the finished machine, whose dimensions and winding data are known. The method applied to a shunt machine, is as follows.

Run the machine at its normal speed of  $n$  revolutions per second, with its full-load of  $C_u$  amperes. Measure the shunt current  $C_m$ , and electromotive-force at terminals  $V$ ; and also note the lead of the brushes. From the resistance of the armature (brush to brush) and the load current, we calculate the ohmic drop as  $R_a \times C_a$ . This added to  $V$  gives  $E$ , the volts actually generated at full-load. The full-load useful flux must hence be

$$N_a = \frac{E \times 10^8}{n \times Z}.$$

Now calculate the ampere-turns required to drive a flux of  $N_a$  lines through the whole magnetic circuit. Call them  $X_1$ . From the known lead of the brushes and the armature current

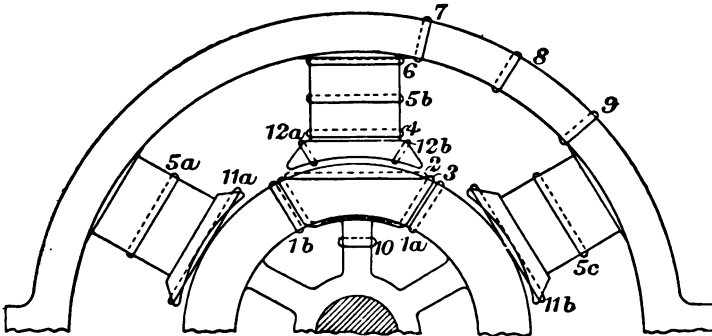


FIG. 6.—ESTIMATION OF LEAKAGE BY EXPLORING-COILS.

calculate the value of the demagnetizing ampere-turns as indicated on page 127. Subtract them from the observed full load ampere-turns  $S_u C_m$ , obtaining a value  $X_2$ . Then the dispersion coefficient is approximately given by

$$v = \frac{X_2}{X_1}.$$

To obtain a nearer approximation, take the value of demagnetizing ampere-turns as calculated, multiply by this value of  $\nu$ , and then subtract from  $S_m C_m$ , obtaining a new value for  $X_2$  to be used as above. But this method as a whole is not capable of giving very accurate results.

A highly detailed examination was made at Schenectady upon a multipolar dynamo, to ascertain the fluxes through the various parts. A large number of exploring coils were wound over the machine as indicated in the accompanying Fig. 6. The results are given in Table V.

TABLE V.—FLUXES IN VARIOUS PARTS OF A DYNAMO.  
M P-6—400—500 (G. E. Co.).

Number of coil Fig. 6.	Flux through that part		
	With 10.5 amperes in field.	With 10.2 amperes in field.	With 32.4 amperes in field.
1a	2,220,000	2,670,000	3,060,000
1b	2,284,000	2,770,000	3,111,000
2	3,660,000	5,465,000	6,180,000
3	3,880,000	5,840,000	6,615,000
4	4,620,000	6,120,000	6,950,000
5a	4,895,000	6,350,000	7,400,000
5b	4,900,000	6,480,000	7,525,000
5c	4,750,000	6,290,000	7,333,000
6	4,830,000	6,470,000	7,385,000
7	2,356,000	3,120,000	3,575,000
8	2,480,000	3,100,000	3,470,000
9	2,500,000	3,120,000	3,500,000
10	34,000	44,200	54,000
11a	3,910,000	5,140,000	6,180,000
11b	4,000,000	5,200,000	6,115,000
12a	498,000	731,000	985,000
12b	473,000	728,000	934,000

Looking at the figures in the last column, with the excitation at its highest, we see that the maximum flux in the pole-core was about 7,400,000 lines. Of these about 6,180,000 actu-

ally entered the armature, the sum of the fluxes measured by exploring coils Nos. 1a and 1b agreeing closely with that of No. 2. The yoke appears to be of insufficient section, as the flux passing through No. 8 is less than half of that through Nos. 5 or 6. Taking the figures above we see that the coefficient of dispersion at the highest excitation is  $\nu = 1 \cdot 19$ .

TABLE VI.—DISPERSION COEFFICIENTS.

Output in kilowatts	Over-type as No. 23, p. 162, D. E. M.	Under-type as No. 2, p. 159.	Single-magnet type, as No. 31, p. 163.	Manchester type, as No. 24, p. 162.	Bi-polar iron-clad type, as No. 25.	Double horse-shoe type, as No. 6, p. 159.	Four-pole iron-clad type, as No. 22, p. 159.	Multi-polar type, as No. 28, p. 162.
1 to 5	1'4	1'6	1'55	1'7	1'30	1'65	1'75	1'5
5 to 25	1'28	1'45	1'4	1'55	1'22	1'5	1'55	1'32
25 to 100	1'22	1'35	1'32	1'45	1'16	1'4	1'45	1'28
100 to 300	..	1'25	..	..	..	..	..	1'22
300 to 1000	..	..	..	..	..	..	..	1'10

Table VI. given above gives the value of the dispersion coefficient for various types and sizes of machines, the values in every case being if anything, in excess of the true amount, as they have been obtained from calculation and experiment under the most unfavourable conditions.<sup>1</sup> Magnetic dispersion is always greater with the smaller sizes of machine, on account

<sup>1</sup> See *Dynamo-machines*, by A. Wiener, 1902. For earlier data on the stray fields of dynamos, see Hering in *El. Rev.*, xxi. 186 and 205, 1887; Carhart, *Electrician*, xxiii. 644, 1889; Wedding, *Electrot. Zeitschrift*, xiii. 67, 1892; Mavor, *Electrical Engineer*, xii. 428, 1894; W. B. Esson in *Journ. Inst. Electrical Engineers*, Feb. 1890; and W. L. Puffer in *Technology Quarterly*, iv. 205, Oct. 1891. Some recent researches on magnetic dispersion are those of Rothert in the *Elektrotechnische Zeitschrift* for May 26, 1898; and Picou, *Bulletin Soc. Internat. des Electriciens*, June 1902, p. 425. Attempts to reduce dispersion are discussed by Kelly in *Electrical World*, xxxii. 161, 1898, and by Guilbert in *L' Eclairage Electrique*, xviii. 298, 1899.

of the difficulty of properly dimensioning the field-system. It is also greater with cast-iron magnets and pole-pieces, and as we have seen already, with smooth core armatures. The values given below may consequently be looked upon as being high for slotted armatures and wrought iron or cast steel fields.

#### CALCULATION OF DISPERSION.

It is possible to predetermine, from the working-drawings of a dynamo before it is built, the probable amount of dispersion. Calculations of the dispersion are based upon the principle that where a circuit offers alternative paths, the magnetic flux will divide itself between the paths in the proportion of their relative facility for flow, exactly as an electric current divides where there are alternative conducting paths. In fact, the law of shunts has been found to hold good for magnetic lines. The reader should consult the researches of Ayrton and Perry<sup>1</sup> on this point. It follows that along any branched part the joint *permeance*<sup>2</sup> (or magnetic conductance) will be the sum of the permeances of the separate paths. Hence, if the permeances of the separate paths of the useful and waste magnetic fluxes of a dynamo are known, the coefficient of dispersion,  $\nu$ , can be calculated, it being the ratio of the total flux to the useful flux. Call the useful flux  $u$  and the waste flux  $w$ ; then

$$\nu = \frac{u + w}{u}.$$

But each of these is a complicated quantity; therefore the more complete formula is

$$\nu = \frac{u_1 + u_2 + u_3 + \dots + w_1 + w_2 + w_3 + \dots}{u_1 + u_2 + u_3 + \dots}$$

In order to determine the separate permeances along the various leakage paths, we must resort to some useful rules or

<sup>1</sup> *Journ. Soc. Teleg. Engineers and Electricians*, 530, 1886.

<sup>2</sup> *Permeance* is of course the reciprocal of magnetic reluctance; just as electric conductance is the reciprocal of electric resistance.

lemmas originally suggested by Professor Forbes,<sup>1</sup> which consist in certain approximate integrations. For the convenience of British engineers the values have been recalculated into inch measures instead of centimetre measures.

The unit reluctance and unit permeance are so chosen as to obviate the subsequent necessity of multiplying the ampere-turns by  $4\pi \div 10$ . This will make the reluctance of the inch cube of air equal to  $10 \div 4\pi$  divided by  $2 \cdot 54 = 0 \cdot 3133$ ; and its permeance to  $3 \cdot 1918$ .<sup>2</sup>

*Rule I.—Permeance between two parallel areas facing one another.* Assume that the magnetic lines are straight and equally distributed over the surface: then,

$$\begin{aligned}\text{Permeance} &= 3 \cdot 1918 \times \text{mean area (square inches)} \div \text{distance} \\ &\quad \text{(inches) between them} \\ &= 1 \cdot 596 \times (A_1'' + A_2'') \div d''.\end{aligned}$$

*Rule II.—Permeance between two equal adjacent rectangular areas lying in one plane.* Assuming the lines of flux to be semicircles, and that distances  $d_1''$  and  $d_2''$  between their nearest and furthest edges respectively are given; also  $a''$  their width along the parallel edge:—

$$\text{Permeance} = 2 \cdot 274 \times a'' \times \log_{10} \frac{d_2''}{d_1''}.$$

*Rule III.—Permeance between two equal parallel rectangular areas lying in one plane at some distance apart.* Assume the lines of flux to be quadrants joined by straight lines.

$$\text{Permeance} = 2 \cdot 274 \times a'' \times \log_{10} \left\{ 1 + \frac{\pi (d_2'' - d_1'')}{d_1''} \right\}.$$

*Rule IV.—Permeance between two equal areas at right-angles to one another.*

Permeance = double the respective values calculated by Rule II.

<sup>1</sup> *Journ. Soc. Teleg. Engineers*, xv. 551, 1886.

<sup>2</sup> See the Author's work *The Electromagnet*.

If measures are given in centimetres these rules become the following:—

- I.  $\frac{1}{2} (A_1 + A_2) \div d$ .
- II.  $\frac{a}{\pi} \text{hyp. log } \frac{d_2}{d_1}$ .
- III.  $\frac{a}{\pi} \text{hyp. log } \left( 1 + \frac{\pi (d_2 - d_1)}{d_1} \right)$ .

Using these rules to predetermine the stray field to fly-wheels, pedestals and shafts, it is possible from the working drawings to predict the performance of a machine to within 2 per cent.

The author has given (in his work on *The Electromagnet*) some further rules, including the case of permeance between two parallel cylindrical limbs. The reader should also consult the writings of Kapp,<sup>1</sup> Wierer<sup>2</sup> and Arnold<sup>3</sup> for the predetermination of the dispersion coefficient, the last named author going into the question at great length.

Goldsborough<sup>4</sup> has laid down the theorem that, assuming a fixed difference of magnetic potential between the surface of a pole-piece and that of an armature core (the latter surface supposed to be smooth), *the intensity of the magnetic field at any point at the surface of the armature will be proportional to the sum of the reciprocals of the distances of that point from all the points on the perimeter of the pole-piece made by a section-plane passing through that point.* On this principle he has calculated the distribution of the flux in the gaps in certain cases.

By definition the dispersion coefficient  $\nu = (N_a + N_s) \div N_a$ ; and as the useful and stray fluxes are respectively proportional to the permeances of the useful and stray paths, if we write  $P_u$  for the permeance through the gap and teeth, and  $P_s$  for the permeance of the stray field, we may write  $\nu =$

<sup>1</sup> *Elektromechanische Konstruktionen*, by G. Kapp, p. 9.

<sup>2</sup> *Dynamo-machines*, by A. Wiener, 1902, pp. 217-265, and 614-628.

<sup>3</sup> *Die Gleichstrom-Maschinen*, 1902.

<sup>4</sup> *Trans. Amer. Inst. El. Engineers*, June 30, 1898, p. 515.

$(P_u + P_s) \div P_u$ . Now  $P_s$  is a constant, being through air, whereas  $P_u$  being partly through air and partly through iron will diminish as the saturation of the teeth increases towards full-load. Hence  $\nu$  will rise as the excitation is increased.

#### DETERMINATION OF EXCITING AMPERE-TURNS.

The calculation of the ampere-turns necessary to drive a certain useful flux  $N_a$  across the air-gap of a dynamo is a straight-forward matter if we know the dispersion coefficient of the machine, and the magnetic properties of the materials used to carry the flux, as laid down in curves such as those in Plate I.

The method of using these curves for the purposes of dynamo calculation is as follows. We are given:—

$N_a$	useful flux per pole.
$A_1$	magnetic area of yoke.
$A_2$	“ of field cores.
$A_3$	“ of air-gap.
$A_4$	“ of teeth under one pole.
$A_5$	“ of armature core.
$L_1$	length of magnetic path in yoke.
$L_2$	“ “ in two field cores.
$L_3$	“ “ in two air-gaps.
$L_4$	“ “ in two teeth.
$L_5$	“ “ through armature core.

and the question is to find the ampere-turns per pair of poles necessary to produce the flux of  $N_a$  magnet lines in the air-gap.

Now the total flux is

$$N_m = \nu N_a.$$

Consequently, by dividing this by the magnetic area of yoke and magnet cores we obtain

$B_1$	flux-density in the yoke.
$B_2$	“ in the magnet cores.



in multipolar machines the yokes will only carry half the total flux, as it will divide each way. The magnetic length is the mean length of path.

(b) *Magnet Cores*.—The magnetic section is simply the section of one core. The magnetic length  $L_2$  is that of two pole-cores.

(c) *Air-gap*.—The length is twice the distance from iron to iron. With regard to the magnetic section to be taken, it is always more or less a matter of judgment and experience, on account of the spreading of the flux from the pole-piece, or *fringing* as it is frequently called. For machines having smooth core armatures, and where the length of pole-piece is equal to the gross length of the armature core, the magnetic area of the air-gap may be taken as the area of one pole-piece *plus* a small area equal to the length of one air-gap multiplied by the periphery of one pole-piece. For machines with slotted armatures, the air-gap area may be taken as the mean of the pole-face area and of the *iron* area at the face of the teeth under one pole. But the number of teeth so reckoned should be increased by one or two over the actual number under one pole, to allow for the fringing; such allowance, depending upon the length of the gap, shape of the teeth at the armature periphery, and flux-density at which they are worked. On account of distortion of the field, the magnetic area of the air-gap may be different at full-load from what it is at no-load, but the two rules above will generally be found good enough.

(d) *Armature Core*.—Here ~~again if the machine is multipolar~~ the core will only have to carry half the useful flux. The magnetic length is the length of the mean path lying between the roots of the teeth and the periphery of the internal hole. The magnetic section is less than the gross section by 10 to 25 per cent., on account of the insulation of the core-disks and the presence of ventilating ducts. If these latter are absent, as is usually the case with small armatures, allow 10 per cent. as space-loss if the disks are varnished, and 15 per cent. if paper insulation is employed. If air ducts are present, their width must be subtracted from the gross length when computing the area. For paper insulated armatures with the usual allow-

ance of ventilating ducts, the nett length of core (parallel to shaft) is generally 75 per cent. of the gross length.

(e) *Teeth*.—The total length of tooth traversed by the flux is equal to the depth of a slot multiplied by 2. The width of one tooth to be taken as the mean width. The number lying under one pole may be taken as the number of teeth in the polar angle plus one or two, depending on the length of the air-gap, in order to allow for spreading. The magnetic area of one tooth will therefore be the mean width of tooth multiplied by the nett length of armature, (that is, gross length minus total width of air-ducts minus 10 to 15 per cent. space lost through insulation). But there is yet an important point. If the teeth are worked at densities of 100,000 lines, or more, per square inch, part of the useful flux will pass into the core by way of the slots, because these offer a path in parallel whose magnetic conductivity is comparable with that of the teeth themselves.

It follows, therefore, that the ampere-turns for the teeth calculated out on the basis that they carry the whole of the flux, will be in excess of the right amount at high values of tooth flux-density. We will now proceed to show how the true value of tooth flux-density  $B_t$  may be estimated if we know the apparent flux-density in the teeth which we will call  $B_a$ . Further, we will denote by

$b_1$  mean width of tooth

$b_2$  width of slot

$l$  nett length of armature, that is, the *iron* length parallel to shaft

$h$  height or depth of slot

$f$  ratio of nett length to gross length of armature core

$N_a$  flux from one pole, as before

$N_t$  flux actually carried by teeth.

Then we have

$$\text{Iron section of one tooth} = b_1 \times l.$$

$$\text{Air " " " slot} = \frac{b_2 \times l}{f}.$$

The actual section of air space per slot forming an alternative path in parallel for the flux is given by the area of one slot *plus* the area of the space lost along one *tooth* by insulation and ventilating ducts, or

$$\begin{aligned} \left. \begin{array}{l} \text{Section of air-space} \\ \text{per slot} \end{array} \right\} &= \frac{b_2 \times l}{f} + (1-f) \frac{b_1 \times l}{f} \\ &= \frac{l(b_1 + b_2 - b_1 f)}{f}. \end{aligned}$$

Now the flux  $N_a$  coming out of the pole-piece will divide itself between tooth and air-space in inverse proportion to the reluctance of these two. The flux in the air-space is  $(N_a - N_i)$ .

Hence we have

$$N_i \propto \frac{b_1 \times l \times \mu}{h},$$

where  $\mu$  is the permeability of the tooth when transmitting the actual flux  $N_i$ .

Also

$$(N_a - N_i) \propto \frac{l(b_1 + b_2 - b_1 f)}{f \times h}$$

and by division

$$\begin{aligned} \frac{N_i}{(N_a - N_i)} &= \frac{f b_1 \mu}{b_1 + b_2 - b_1 f} \\ N_i (b_1 + b_2 - b_1 f + b_1 f \mu) &= N_a f b_1 \mu \\ \frac{N_i}{N_a} &= \frac{f b_1 \mu}{b_1 + b_2 - b_1 f + b_1 f \mu} = \frac{B_i}{B_a}. \end{aligned}$$

As stated above, a common ratio of iron length to gross length for slotted armatures with air-ducts and paper insulation is 0.75. Putting in this value of  $f$  in the above equation we have

$$\begin{aligned} \frac{B_i}{B_a} &= \frac{0.75 \times b_1 \mu}{b_1 + 0.25 b_1 + 0.75 b_1 \mu} \\ \text{or} \quad \frac{B_i}{B_a} &= \frac{b_1 \mu}{1.34 b_1 + 0.33 b_1 + b_1 \mu}. \end{aligned}$$

To put this into practical shape, take ratio of  $b_1$  to  $b_2$

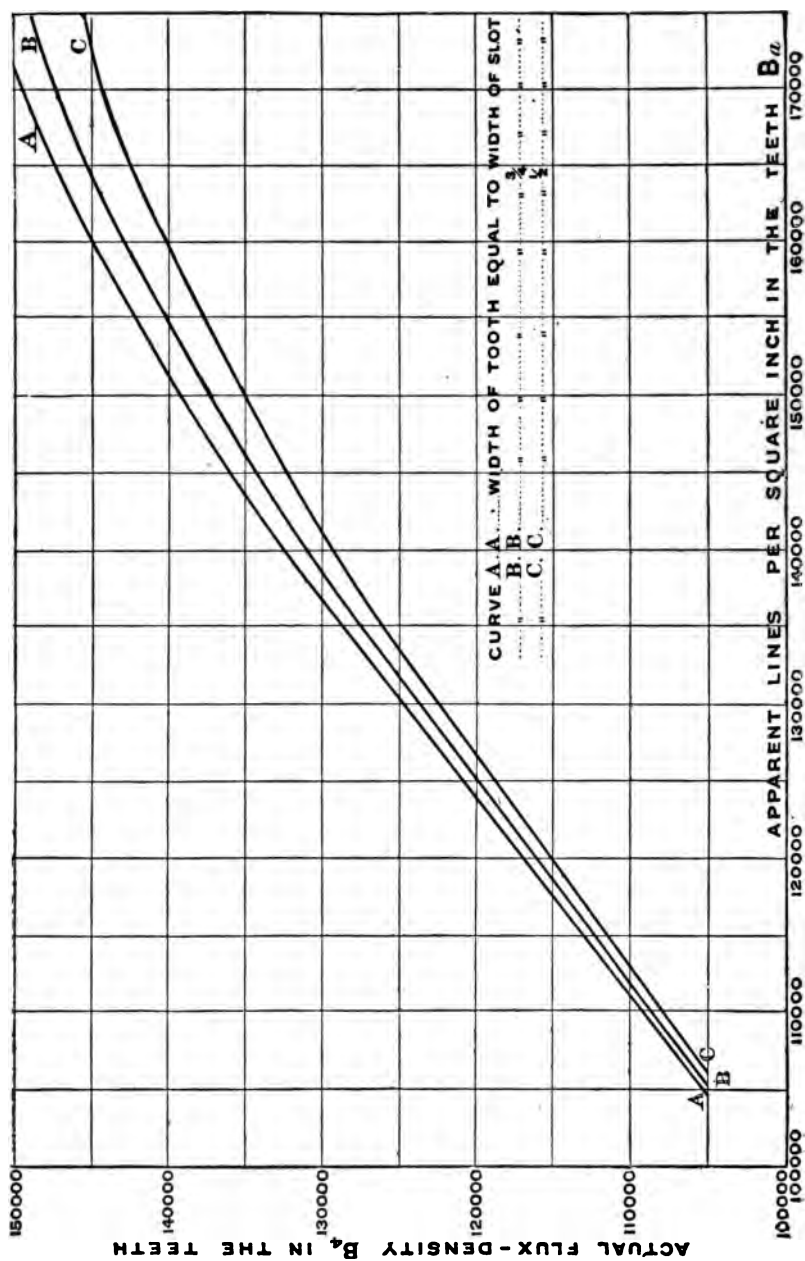


FIG. 7.—APPARENT AND ACTUAL FLUX-DENSITIES IN TEETH.

assume values for  $B_4$ , find the corresponding permeabilities from such a curve as that of Fig. 1 and calculate  $B_a$ . Then a curve connecting  $B_a$  and  $B_4$  for this particular ratio of  $b_1$  to  $b_2$  can be plotted, showing what the true flux-density in the teeth is when the apparent flux-density (that is, total flux per pole divided by iron area of teeth under one pole, or  $N_a \div A_4 = B_a$ ) has any particular value. This has been done in the three curves shown in Fig. 7 for three usual ratios of  $b_1$  to  $b_2$  using the above equation. If  $f$  has a value different from 0.75, the equation should be correspondingly altered and new curves plotted when great accuracy is desired.

#### EXAMPLE OF CALCULATION.

In order that the foregoing rules may be clearly understood, and to exemplify the use of the curves, etc., we will take a concrete case for purpose of illustration. In Fig. 8 is given a dimensioned sketch of part of a modern six pole 200 kilowatt machine. We will proceed to calculate how many ampere-turns per pair of poles are required in order to produce a flux of 12,500,000 lines through the air-gap.

A reference to the table of dispersion coefficients on page 23 gives us an approximate figure,

$$v = 1.18,$$

and hence,

$$N_m = N_a \times 1.18 = 14,750,000.$$

The next thing to do is to make an estimate of the magnetic lengths and areas. We have

Yoke.

$$\text{Area} = 17.5 \times 5$$

$$A_1 = 87.5 \text{ square inches.}$$

For the length of mean path, we can either scale it off from the drawing, which is, as a rule, more convenient, or estimate it from

$$\begin{aligned} L, &= 5 + \left\{ \frac{(59.9 + 33.5 + 5) \times 3.14}{6} \right\} \\ &= 56.5 \text{ inches.} \end{aligned}$$

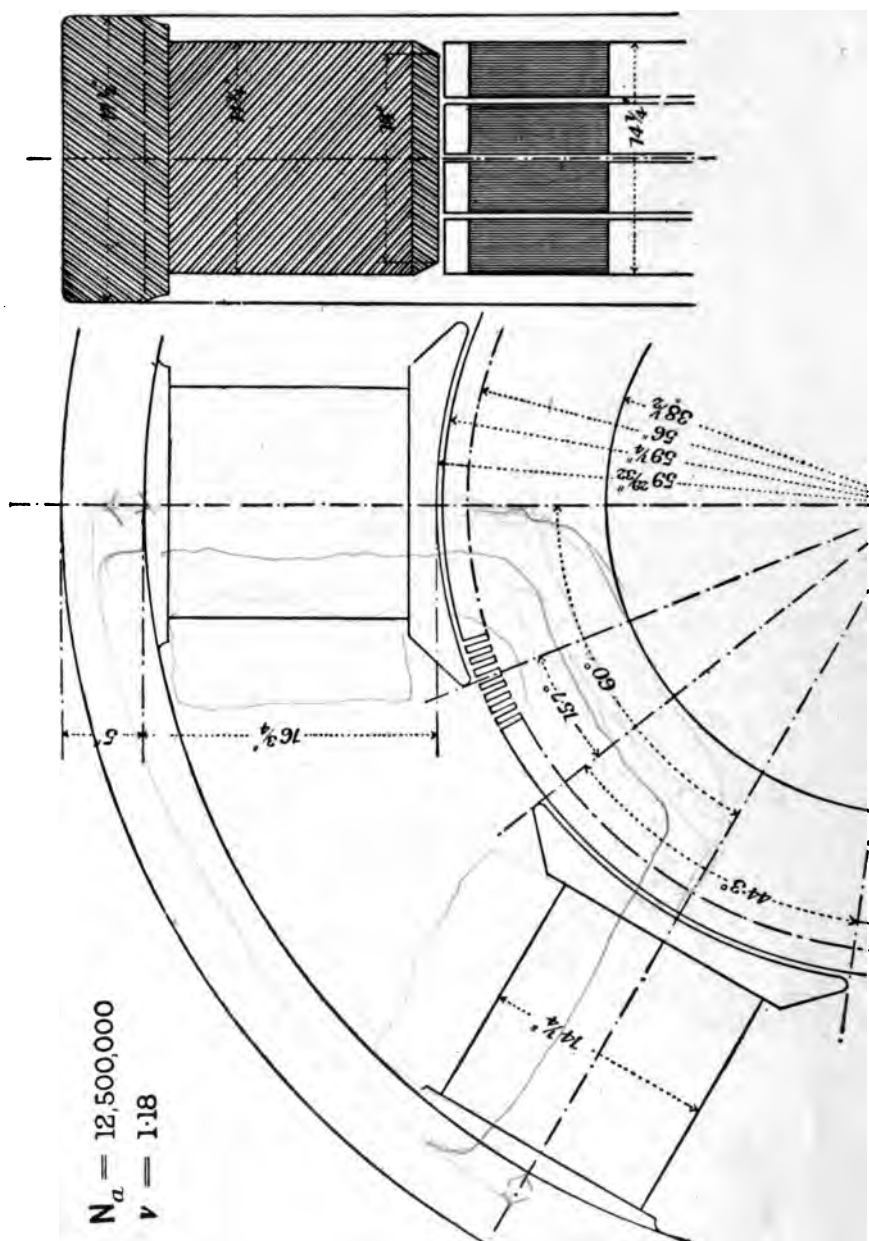


FIG. 8.—MAGNETIC CIRCUIT FOR CALCULATION.

As no allowance has here been made for the rounding off of corners along the mean path taken by the flux, we may say

$$L_1 = 55.$$

*Magnet Cores.*—As these are circular, we have

$$\begin{aligned} A_2 &= 14.25 \times 14.25 \times 0.785 \\ &= 159.5 \text{ square inches.} \end{aligned}$$

The magnetic length of the two cores and pole-pieces is

$$L_2 = 2 \times 16.75 = 33.5.$$

*Air-gaps.*

$$\begin{aligned} L_3 &= 59.9 - 59.25 \\ &= 0.65 \text{ inch.} \end{aligned}$$

For the area, we take, as stated above, the mean between pole-piece area and the area of the teeth under one pole at their tops. As the air-space in this machine is short, we take for the number of teeth acted on by one pole the actual number lying in the polar angle, *plus one*. Had the air-space been longer we should have added *two*.<sup>1</sup>

From the sketch we see that the polar angle is  $44.3^\circ$ . As there are altogether 220 teeth, the number in the actual polar angle is

$$220 \times \frac{44.3}{360} = 27.$$

Adding one to this, we have 28 as the number transmitting the flux. Now the iron area of a single tooth at the top is

$$\begin{aligned} &\{ 14.25 - (3 \times 0.375) \} \times 0.9 \times 0.429 \\ &= 5.06 \text{ square inches.} \end{aligned}$$

<sup>1</sup> This allowance for the *fringing* of the magnetic field, which increases the useful flux entering the armature from one pole, is a matter of judgment and experience. Fischer-Hinnen has given elaborate rules. For smooth-cored armatures it is usual to estimate the width of the fringe as equal to the gap from iron to iron. See a paper also by Sander in the *Zeitschrift für Elektrotechnik*, xviii, 562, Nov. 1900.

The iron area at the top of the teeth under one pole is hence

$$28 \times 5.06 = 142 \text{ square inches.}$$

And the area of the pole-face is

$$13 \times \left( 59.9 \times 3.1416 \times \frac{44.3}{360} \right) \\ = 302 \text{ square inches.}$$

Hence, we have for the magnetic area of the air-space,

$$A_s = \frac{142 + 302}{2} = 222 \text{ square inches.}$$

*Teeth.*—For the magnetic length we have

$$L_4 = 2 \times 1.625 = 3.25 \text{ inches.}$$

And the mean iron area of the 28 teeth acted upon by one pole is

$$\{14.25 - (3 \times 0.375)\} \times 0.9 \times 0.406 \times 28, \\ A_4 = 134.5 \text{ square inches.}$$

*Armature Core.*—The mean length of the path taken by the flux is best obtained from the drawing; otherwise we have

$$8.75 + \left\{ \left( \frac{56 + 38.5}{2} \right) \times 3.146 \times \frac{1}{6} \right\} \\ = 33.55 \text{ inches.}$$

Or say  $L_5 = 33$  inches.

The magnetic area is

$$\{14.25 - (3 \times 0.375)\} \times 0.9 \times 8.75, \\ A_5 = 103.5 \text{ square inches.}$$

Having now found the magnetic dimensions, we can construct the table given below. The flux-densities have been obtained by dividing the flux in each part by the corresponding magnetic area; as the density in the teeth is in this case below 100,000, we may assume that no correction is necessary—that is, we may consider  $B_a = B_4$ , the entire flux being carried

by the teeth. The rest of the working is sufficiently obvious, the final result being that to force the 12·5 megalines through the iron and across the gaps, something over 14,000 ampere-turns per pair of poles are required. The actual number would be taken in practice as 15,000 at least, in order to allow for differences in the iron, etc.

$$N_a = 12,500,000; N_m = 14,750,000; \nu = 1 \cdot 18.$$

Part of machine.	Material.	Magnetic Length.	Magnetic Section.	Flux-Density.	Value of $\delta$ from Curves.	Ampere-turns Required.]
Yoke	Cast steel	55	87·5	84100	24·2	1330
2 Magnet cores	Ditto	33·5	159·5	92500	32·5	1090
2 Air-gaps	Air	0·65	222	56300	$\times 0 \cdot 3133^*$	11500
2 Teeth	Sheet iron	3·25	134·5	93000	19	62
Armature core	Ditto	33	103·5	60400	4	132

Total ampere-turns per pair of poles = 14114.

By similar calculations we can find the ampere-turns required to force other values of  $N_a$  across the air-gap and through the iron parts of the machine. By plotting the values of excitation so obtained against the corresponding values of  $N_a$ , we obtain what is known as the *saturation curve*, of the magnetic circuit in question; the ordinates of the curve representing also the corresponding values of the induced electromotive-force to a different scale. Examples of such calculated curves will be found in Chapter VIII. on Examples of Dynamo Design.

\* This number 0·3133 is the *gap-coefficient* and represents the number of ampere-turns per inch length of path requisite for a flux-density of 1 line per square inch. Multiplying the flux-density of the preceding column by this coefficient gives the number of ampere-turns needed for that density, per inch of path in air; and multiplying this number by the magnetic length of the 2 air-gaps, in column 3, gives finally the number of ampere-turns needed for the 2 gaps.

$$56300 \times 0 \cdot 3133 \times 0 \cdot 65 = 11500.$$

We have here calculated the ampere-turns needed for a pair of poles; but as the two halves of the magnetic circuit so considered are alike, one may, if preferred, calculate simply the ampere-turns *per pole*, taking only one-half of a magnetic circuit, including, of course, one gap, one pole-core, etc., and taking yoke and armature core at half the lengths estimated as above. A convenient form of schedule for such calculations will be found in Appendix I.

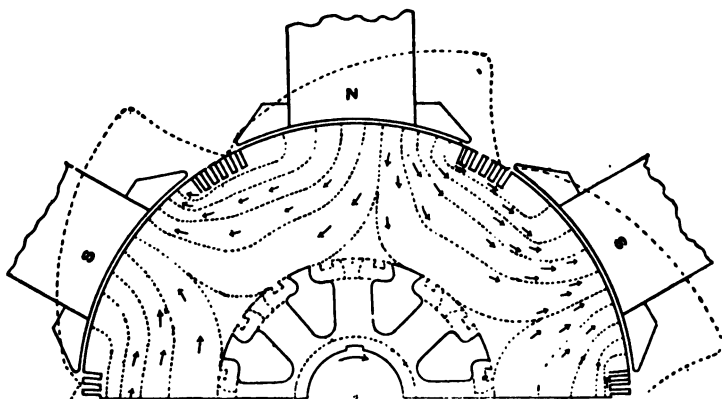


FIG. 9.—CORE-DISTRIBUTION OF FLUX.

In a careful study, in part theoretical, but confirmed by experiments, Goldsborough<sup>1</sup> has shown that in the armature of a multipolar dynamo the paths of the magnetic lines through the armature core are not symmetrical, and that they are not distributed with equal density through the cross-section of the core (Fig. 2), being denser in the region immediately below the roots of the teeth, and less dense near the internal circumference of the core. At full load these inequalities are more marked. As a consequence any calculations as to hysteric losses in the core made on the assumption of uniform distribution will understate the actual waste of energy.

<sup>1</sup> Air-gap and Core Distribution Studies, *Trans. Amer. Inst. El. Engineers*, June 1899, p. 461.

Similarly, Mr. Dettmar has shown in the *Elektrotechnische Zeitschrift* for 1900, vol. xxi. 944, that the density of the flux in the core-body diminishes, not quite in arithmetical proportion, from a maximum below the roots of the teeth to a minimum at the internal periphery.

If the pole-pieces are not laminated, the width of the gap should not be much less than about  $1\frac{1}{2}$  times the width of the slot, otherwise the unequal distribution of the flux at the pole-face will set up harmful eddy-currents.

Professors H. Hele-Shaw and A. Hay have published in the *Philosophical Transactions*, cxcv. 303, 1900, a very remarkable paper on lines of induction in a magnetic field, the distribution of which they have studied by the aid of a beautiful hydraulic model in which the stream-lines in glycerine imitate the forms of the magnetic lines under varying conditions. Amongst these they show the distribution in the case of a toothed armature with a gap approximately equal to the breadth of a tooth and with slot slightly wider. In the gap the density of the lines shows alternate maxima and minima, the lines being very slightly curved at the level of the teeth; but below this level those that enter the slot swerve sharply round to enter the flanks of the teeth.

Except in the case of very highly saturated teeth, there is no field in the slot at any greater depth than about equal to the slot width. The ratio of the density of the field in the slot to the density of field in the tooth is roughly the same as the ratio of the gap-length (from iron to iron) to the sum of gap-length and tooth length.

Herr Dick has shown, in the *Electrotechnische Zeitschrift* for July 1901, that if account is taken of the flux-densities along the tooth, the ampere-turns actually needed will be considerably less than the number (only about %) calculated from the mean between the maximum value at the roots and the minimum value at the tops of the teeth. In the same journal for November 1901, Dr. Coosepius has shown how the design of armatures is dependent on the ratio between the width of the tooth and the width of the slot.

## CHAPTER III.

## COPPER CALCULATIONS: COIL WINDINGS.

*Weight of Copper Wire.*—Pure copper has a specific gravity of 8·9 at the ordinary atmospheric temperature of 15° C. Hence

1 cubic centimetre	weighs 8·9 grammes;
1 cubic foot	“ 555 pounds;
1 cubic inch	“ 0·3213 pounds.

A rod of copper 1 inch in diameter, and 1 foot in length weighs 3·028 lbs. Hence the weight of a copper wire can be found by multiplying together its length in feet, its sectional area in square inches, and the coefficient 3·028. A wire 1 mil in diameter and 1 foot long weighs 0·000003028 lb. Hence if  $d$  be the diameter in *mils*, and  $l$  the length in *feet*, the weight of the wire will be

$$\text{weight in lbs.} = d^2 \times l \times 0\cdot000003028;$$

$$\text{or a wire } d \text{ mils in diameter weighs } \frac{d^2}{330250} \text{ lbs. per foot.}$$

*Example.*—30 feet of a No. 1 S. W. G. copper wire, which is 300 mils in diameter, weighs 8·17 lbs.

In the case of copper strip of rectangular section if the width and depth of the strip are given in mils, and the length in feet, the weight in pounds can be found from the rule that weight in lbs. = sectional area in sq. mils  $\times l \times 0\cdot000003855$ .

*Electric Resistance of Copper.*—Pure copper has a specific resistance that increases slightly with temperature.

The resistance of a centimetre cube of pure copper, in ohms, has the following values:—

	At 0° C.	At 15° C.	At 30° C.	At 60° C.
Annealed	0'00000159039	0'00000169259	0'00000179559	0'00000200401
Hard-drawn	0'00000162246	0'00000172676	0'00000183180	0'00000204442

	At 32° F.	At 60° F.	At 115° F.
Annealed	0'00000159039	0'00000169639	0'00000198847
Hard-drawn	0'00000162246	0'00000173054	0'00000202856

The rise of resistance of copper with temperature is approximately  $\frac{1}{10}$  of one per cent., per Centigrade degree, or  $\frac{2}{3}$  of one per cent. per Fahrenheit degree.

If the resistance  $R_{0^{\circ}\text{C.}}$  at freezing-point, of any copper conductor be known, its resistance  $R_{\theta^{\circ}\text{C.}}$  at any temperature  $\theta$  on the Centigrade scale, can be accurately calculated by the formula of Clarke, Forde and Taylor:

$$R_{\theta^{\circ}\text{C.}} = R_{0^{\circ}\text{C.}} \{1 + 0'00426744\theta + 0'0000011193\theta^2\};$$

or on the Fahrenheit scale,

$$R_{\theta^{\circ}\text{F.}} = R_{32^{\circ}\text{F.}} \{1 + 0'0023708(\theta - 32) + 0'00000034548(\theta - 32)^2\}.$$

The following are some useful rules for calculating the resistances of copper as used in construction of electric machines. In all cases it is assumed that the material is pure annealed copper, commonly called "high conductivity" copper. If the copper is "hard drawn" instead of "annealed" the resistance may be some 2 per cent. greater for an equal cross-section and equal length. Resistances are given in ohms.

*British Units.*—Resistance of 1 inch cube is

0'00000062615	at 0° C. or 32° F.
0'00000066639	at 15° C.
0'00000066788	at 60° F.
0'00000070694	at 30° C.
0'00000075085	at 115° F.
0'00000078899	at 60° C.

A rod of copper, 1 foot long and 1 square inch in cross-section, has the following resistance:—

0·0000075138	at	0° C.
0·0000079966	at	15° C.
0·0000084833	at	30° C.
0·0000094679	at	60° C.

A rod of round copper, 1 foot long and 1 inch in diameter (having therefore a sectional area of 1 circular inch), has the following resistance:—

0·0000095664	at	0° C.
0·0000110812	at	15° C.
0·0000108007	at	30° C.
0·0000120545	at	60° C.

A wire of copper, 1 foot long and having a sectional area of 1 square mil, has the following resistance:—

7·5138 ohms	at	0° C.
7·9966	at	15° C.
8·4833	at	30° C.
9·4679	at	60° C.

A round wire of copper, 1 foot long, having a diameter of 1 mil (and therefore having a sectional area of 1 circular mil), has the following resistance:—

9·5664 ohms	at	0° C.
10·1812	at	15° C.
10·8007	at	30° C.
12·0545	at	60° C.

The resistance of a *copper strip*, the length of which is given in feet and the sectional area in square mils, may therefore be calculated by the rule:—

At 0° C.	ohms per foot	= 7·5138	} divided by area in sq. mils.
At 15° C.	"	= 7·9966	
At 30° C.	"	= 8·4833	
At 60° C.	"	= 9·4679	

The resistance of a *round copper wire*, the length of which is given in feet and the diameter in mils (which diameter, if squared, gives the sectional area in circular mils) may therefore be calculated by the rule:—

At 0° C.	ohms per foot	= 9·5664	} divided by diameter squared.
At 15° C.	"	= 10·1812	
At 30° C.	"	= 10·8007	
At 60° C.	"	= 12·0545	

*Metric Units.*—A rod of copper, 1 metre long and of 1 square millimetre cross section, has the following resistance:—

0·0159039 ohms	at 0° C.
0·0169259	at 15° C.
0·0179559	at 30° C.
0·0200401	at 60° C.

A round wire of copper, 1 metre long and 1 millimetre in diameter, has the following resistance:—

0·0202487 ohms	at 0° C.
0·0215499	at 15° C.
0·0228614	at 30° C.
0·0255148	at 60° C.

The resistance of a *copper strip*, the length of which is given in metres and the sectional area in square millimetres, may therefore be calculated by the rule:—

At 0° C.	ohms per metre	= 0·0159039	} divided by sq. milli- metres.
At 15° C.	"	= 0·0169259	
At 30° C.	"	= 0·0179559	
At 60° C.	"	= 0·0200401	

The resistance of a *round wire* the length of which is given in metres and the diameter in millimetres may be calculated by the rule:—

At 0° C.	ohms per metre	= 0·0202487	} divided by diameter squared.
At 15° C.	"	= 0·0215499	
At 30° C.	"	= 0·0228614	
At 60° C.	"	= 0·0255148	

*Example I.*—To find the resistance at 60° C. (warm) of a copper strip 9·5 feet long, the rectangular section of which measured bare is 118 mils by 785 mils. The product of 118 and 785 gives as the sectional area 92630 sq. mils. Hence by the rule given above the resistance of one foot length is  $9\cdot4679 \div 92630 = 0\cdot0010222$  ohm. Therefore the resistance of 9·5 feet at this temperature is 0·00971 ohm.

*Example II.*—To find the resistance at 60° C. (warm) of a shunt coil of 3050 turns of a round copper wire, No. 16 S.W.G., the mean length of one turn being 5·21 feet. No. 16 S.W.G. has a diameter of 64 mils, therefore a sectional area of  $64 \times 64 (= 4096)$  circular mils. Hence by the rule the ohms per foot will be 12·0545 divided by 4096 = 0·002936 ohm. So the total length being 15890 feet, the total resistance will be 46·65 ohms.

The following rules are useful for copper wires at 30° C.:

$$\begin{aligned} \text{Section in sq. mils} &= 10\cdot8 \times \text{length in feet} \div \\ &\quad \text{resistance in ohms.} \\ \text{Length in feet} &= \text{section in sq. mils} \times \text{re-} \\ &\quad \text{sistance in ohms} \div 10\cdot8. \\ 8483 \div \text{section in sq. mils} &= \text{resistance per 1000 feet} \\ &\quad \text{of length.} \end{aligned}$$

*Electrical Measurement of Temperature.*—If the rise of temperature of an armature or of a field-magnet coil is measured at the surface by the common process of laying upon it the bulb of a thermometer covered with a pad of cotton wool, the temperature so measured will not be the true temperature of the interior, but considerably below the true average temperature of the armature or coil. If the resistance of the coil is measured, then the true internal temperature can be ascertained, provided the resistance of the coil at 0° C., or at 15° C. is known. For practical purposes a near enough approximation can be found by the formula:—

$$\text{Rise in degrees Centigrade} = 237 \frac{R' - R}{R};$$

where R is the resistance as measured when cold, and R' the resistance as measured when hot.

*Stranded Copper Conductors.*—Stranded copper wires are seldom now used in dynamo construction; but compressed stranded conductors are still occasionally found in smooth-cored armatures. An example is furnished by the toothed-cored armatures of the motors of the Central London Railway in which are employed conductors made of 49 strands of No. 19 B. and S. gauge, having an apparent cross section of 0.060 sq. inch. Now 1 such wire has a section of 0.00101 sq. inch, and 49 would therefore have 0.0495 sq. inches in total. But allowance must be made for the increased length due to twisting of the strands, and experiment shows the conductor to have such a resistance that its equivalent section would be only 0.046.

#### SPACE-FACTOR.

In all cases where insulated windings, whether of wire or strip, are used, it is obvious that the copper section in any slot or tunnel through the core disks does not occupy the whole of the space, and the fraction of the space occupied obviously depends upon the thickness of insulation, and upon the shapes of the slots and of the conductors. The ratio of the nett cross-sectional area of the copper in a slot to the gross cross-sectional area of the slot is called the *space-factor*.

*Space-Factor in Armatures.*—The insulation within a slot consists of two parts: that which is employed as a lining to the slot to protect the iron from contact with the conductors, and that which surrounds the individual conductors to protect them from contact amongst themselves. The slot-lining must be relatively thick, because the iron core must be insulated from the full voltage of the machine, while the insulation around the individual conductors may be much thinner, as the difference of potential between any conductor and its neighbours will only be a small fraction of the full voltage. If every conductor had a slot to itself each slot must be lined with the thicker insulation; whereas if several conductors are placed in one slot, one stout lining will surround them all, and a larger fraction of the area of the slot will be filled with copper. The space-factor is therefore higher if the conductors

are so grouped. In the lighting generator of Scott and Mountain, p. 160, working at 250 volts, the area of the slot is 0·65 square inch. The total area of section of the four copper conductors in the slot is 0·308, so that the space-factor is 0·473. Suppose the case of a conductor, the section of which was  $500 \times 150$  mils, having therefore a sectional area of 75,000 square mils. Let this be overwound with thin insulating tape to a thickness of 15 mils, making the dimensions, covered, 530 and 180 mils: its gross sectional area will be 95,400 square mils. Now suppose that to insulate it properly from the iron core a paper and mica insulation 60 mils thick all round is necessary, the slot area for one such conductor must be obviously increased to  $650 \times 300 = 195,000$  square mils at the very least. In practice it will be more, as there is usually a little extra space allowed for packing, and for a wedge under the binding wires. The space-factor cannot possibly exceed 0·395. But if four such conductors are put together, and the thicker insulation simply surrounds the group, the area of slot will have to be at least  $1180 \times 480 = 566,400$  square mils, and the maximum space-factor will be raised to 0·529.

The space-factors in the armatures of some 500-volt machines are as follows:—Oerlikon Co.'s machines 0·6, 0·727, and 0·8; Parshall's 10-pole 0·6; Kolben's 6-pole and 10-pole 0·417 and 0·516; Ganz's 6-pole 0·412; Hobart's large generators 0·46, 0·49, and 0·51.

In a series of 550-volt generators designed by Mr. S. H. Short, ranging from 200 to 1100 kilowatts, the space-factor ranged from 0·423 to 0·533, with a mean value of 0·45.

Of machines at other voltages:—

Brown, Boveri and Co.'s 350 volt, 0·32; 1000 volt (page 204), 0·214; 120 volt 0·505.

Thury's metallurgical machines (page 224), 0·53 and 0·57.

Kolben's 4-pole at 260 volts 0·506; 18-pole at 115 volts 0·53.

Mr. Rothert states that in a series of 240-volt machines of all sizes, the space-factor of the magnet coils varied from 0·5 to 0·7.

In the case of high-voltage machines, particularly alter-

nators, the space-factor is greatly reduced. The following example, due to Herr Kando, illustrates modern practice.

In Fig. 10 are shown three separate cases where slots of the same size are filled. In *a*, for a 500 volt machine there are 4 conductors each of 103.5 square mm. section; or in total 414 square mm. of copper. Each is separately surrounded with its own covering 1 mm. thick. The area of the slot is 668 square mm. So the space-factor is 0.63. In *b*, for 3000 volts there are 24 round wires, each 3 mm. in diameter, each also covered to a thickness of 1 mm. The slot lining must be about 4 mm. thick. The total section of copper

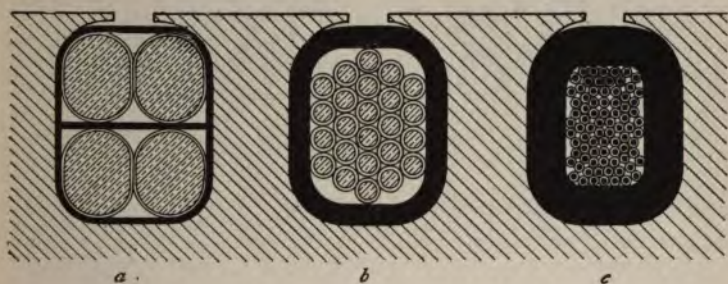


FIG. 10.—SLOT-SPACE AT DIFFERENT VOLTAGES.

is 170 square mm., and the space-factor has fallen to 0.25. In *c*, for 10,000 volts there are 80 wires, each 0.8 mm. diameter, with individual coverings 0.8 mm. thick. The slot-lining must be increased in thickness to about 6 mm. The total section of copper has fallen to 40 square mm.; and the space-factor to 0.06.

*Space-Factor in Field-Magnets.*—In winding bobbins for field-magnets the space-factor is determined largely by the question whether round wires, or wires of square or rectangular section are used. In cases where rectangular wires are employed there is less waste space: and moreover there is a great gain in avoiding such waste space as that which fills the interstices between the wires, whether air or insulating material. Insulation is always a bad conductor of heat, and prevents the internally generated heat from escaping as quickly as it should. Of all non-conductors of heat, entangled air is the

most perfect, witness the non-conducting properties of felt, eider-down, etc. Therefore square or rectangular wire should always be used if possible.

If round wires are used, the space-factor will be determined chiefly by the relative thickness of the wires and of their insulating covering; but it will also be affected by the question of the partial bedding of the wires of one layer between those of the layer beneath. Suppose the wires to lie in precisely square order, without bedding, as in Fig. 11; then if the di-

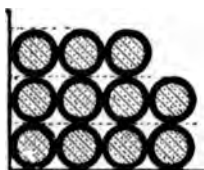


FIG. 11.  
SQUARE ORDER OF BEDDING.

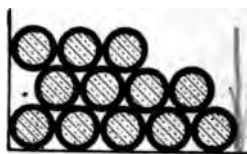


FIG. 12.  
HEXAGONAL ORDER OF BEDDING.

ameter of the bare wire is  $d$ , and that of the wire covered is  $d_1$ , then since the area of each small circle is  $0.7854d^2$ , and as the area of the small square enclosing the outer circle is  $d_1^2$ , the ideal space-factor would be

$$\sigma = 0.7854 \frac{d^2}{d_1^2}.$$

Or, with an infinitely thin insulation it could never exceed 0.7854.

Suppose however an extreme case of bedding, as in Fig. 12, so that the wires lay in hexagonal order like the cells of a honeycomb, the space-factor then would be

$$\sigma = 0.906 \times \frac{d^2}{d_1^2};$$

or with infinitely thin insulation would be 0.906.

If rectangular strip is used, uniformly covered, there is no bedding and no idle space save at the ends of a layer where the coil ascends to the next layer. If the breadth and thickness of the bare strip are called  $a$  and  $b$ , and when covered  $a_1$  and  $b_1$ , the space-factor is simply  $a b \div a_1 b_1$ . Edge-wound

strip has the highest space-factor of any winding. Messrs. Ferranti find it to range from 0.83 to 0.93.

Now, in practice, there is with round wires very little bedding. Some writers have assumed 10 per cent., others 15 per cent. But this is far beyond the facts. Especially in the case of bobbins of small diameter the wire refuses to bed; since, as the successive layers are wound from right to left, and then left to right, each turn must at some point ride over a turn in the layer below it. Bedding, even in the hand of an experienced winder, seldom exceeds 3 per cent. The safest course is to assume that there will be no bedding at all and to take the space-factor, if not known from actual experience, as given by the formula above.

For the shunt-windings of dynamos of standard types at say 500 volts, the space-factor has values seldom below 0.45. This is the figure for the Scott and Mountain 6-pole machine, on p. 160; the Kolben 10-pole machine, p. 216, has 0.60. Mr. Mavor gives values from 0.43 to 0.505 for the magnets of Mavor and Coulson Dynamos.

Some actual figures are given by Dr. S. S. Wheeler for a number of different wires insulated to different thicknesses.

These are exhibited graphically in Fig. 13, the full curves representing the observed values, and the dotted curves the values by the formula assuming square order. It is seen that the larger sizes of wire do actually bed a little, giving a space-factor slightly higher than the calculated value.

*Calculations of Bobbin-Winding.*—The space-factor is closely connected with another important quantity, namely *the resistance per cubic inch of the winding*. By this expression is meant the total resistance of the winding divided by the number of cubic inches of volume which it fills. Suppose a wire covered to the thickness of 100 mils to be wound on a bobbin. There will be 10 wires side by side per inch length of the bobbin, and (if no bedding is assumed) there will be 10 layers per inch thickness, therefore, 100 wires through the square inch of cross-section. A cubic inch taken orthogonally (neglecting curvature) would therefore contain 100 wires each one inch long, and if these were joined in series with one

another, the total amount of resistance within that cubic inch would clearly be 100 times the resistance per inch. If  $\delta_1$  be the diameter of the insulated wire, then  $1/\delta_1^2$  will be the number that go to a square inch of the winding section. Hence if we know the resistance per inch of the copper wire used, the resistance per cubic inch of the winding can be found by

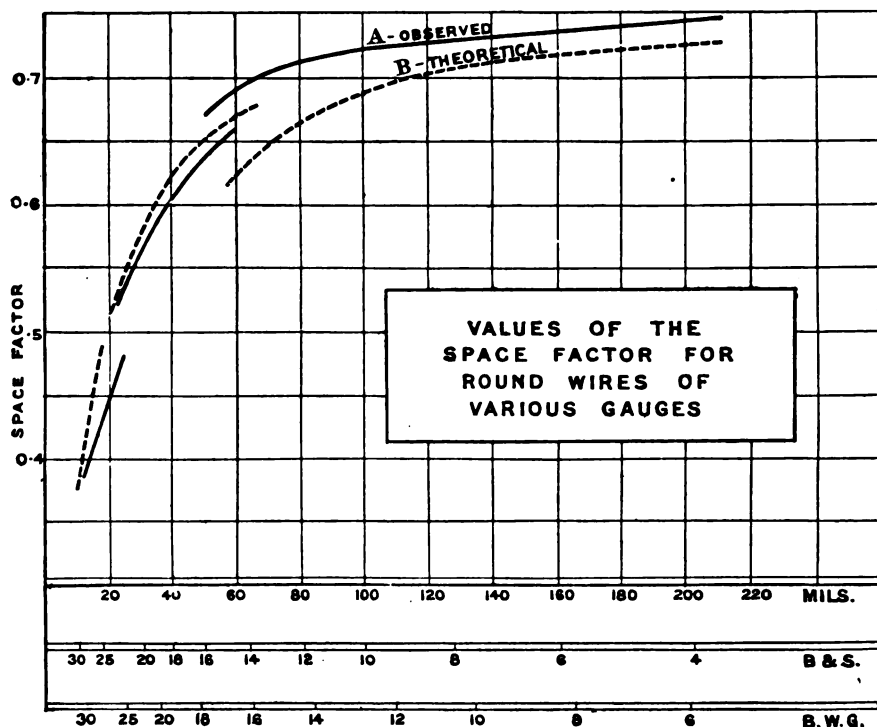


FIG. 13.—SPACE-FACTOR FOR WIRES OF DIFFERENT THICKNESSES.

dividing it by the square of the diameter of the covered wire. If the diameter of the bare wire is given in mils, we have:—

$$\begin{aligned}
 \text{Resistance per inch at } 15^\circ \text{ C} &= 0.8484 \div \text{diameter squared} \\
 \text{" " } 30^\circ \text{ C} &= 0.9001 \div \text{diameter squared} \\
 \text{" " } 60^\circ \text{ C} &= 1.045 \div \text{diameter squared}
 \end{aligned}$$

Or, if the diameter bare,  $d$ , and the diameter covered,  $d_1$ , be

expressed in mils, the resistance of one cubic inch of the winding will be given by the formula:—

$$\rho_1 = \frac{0.8484}{d^2 \times d_1^2} \text{ at } 15^\circ \text{ C.}$$

$$\rho_1 = \frac{0.9001}{d^2 \times d_1^2} \text{ at } 30^\circ \text{ C.}$$

$$\rho_1 = \frac{1.045}{d^2 \times d_1^2} \text{ at } 60^\circ \text{ C.}$$

This assumes, of course, square order in the winding, the space-factor in this case being  $\frac{\pi}{4} \cdot \frac{d^2}{d_1^2}$ .

If the number of turns of wire in the coil be  $S$ , and the area of the winding space be  $L \times T$ , the number of wires through a square inch of the winding space will be  $S/LT$ . If we multiply the resistance per inch cube of copper by the square of this number, and divide by the space-factor we shall obtain the resistance of one cubic inch of the winding: or

$$\rho_1 = 0.000,000,666 \frac{S^2}{L^2 T^2 \sigma} \text{ ohms at } 15^\circ \text{ C.}$$

$$\rho_1 = 0.000,000,707 \frac{S^2}{L^2 T^2 \sigma} \text{ ohms at } 30^\circ \text{ C.}$$

$$\rho_1 = 0.000,000,789 \frac{S^2}{L^2 T^2 \sigma} \text{ ohms at } 60^\circ \text{ C.}$$

It will be noted that for a given number of turns of wire in a bobbin of given winding space, the resistance per cubic inch, as well as the total resistance, will vary inversely as the space-factor.

*Example.*—A bobbin, of which the nett winding-space is 10 inches long and  $1\frac{1}{2}$  inches deep, is to be wound with 540 turns of wire. Assuming a space-factor of 0.6, the resistance per cubic inch, at  $60^\circ \text{ C.}$ , will be  $0.000000789 \times 540 \times 540 \div (15 \times 15 \times 0.6) = 0.001704 \text{ ohm.}$  And if the mean length of one turn is 44 inches, the total volume will be  $10 \times 1\frac{1}{2} \times 44 = 660 \text{ cubic inches, making the total resistance } 1.125 \text{ ohms.}$

*To find the proper gauge of wire to fill a given bobbin to a prescribed resistance.*—Dividing the prescribed resistance by the volume of the winding space, one obtains the number of ohms per cubic inch. Reference to a table of wires with various thicknesses of covering for which the values are known, will enable the proper gauge to be picked out. For such *Wire-Gauge Tables* see the Appendix.

*To find the proper gauge of wire to carry a given current.*—Suppose, as in the case of a shunt machine, one can estimate beforehand the permissible current, by dividing the permissible number of watts wasted on excitation by the voltage of the dynamo, one may then estimate the gauge of the wire required by knowing what is a suitable ampere-density. In stationary coils a density of 600 to 900 amperes per square inch is customary. (This is roughly from 1 to  $1\frac{1}{2}$  amperes per square millimetre.) (Otherwise stated, one allows from 1100 to 1666 square mils per ampere, or 1400 to 2100 circular mils per ampere.

*Example.*—Estimate the gauge of wire required for the magnets of a 300 kilowatt shunt dynamo at 500 volts. Assume that one can afford a 1 per cent. waste of energy, or 3000 watts. At 500 volts this is 6 amperes. The wire, at 600 amperes per square inch, will require  $\frac{1}{60}$  of a square inch or 12,566 circular mils section. Reference to wire gauge tables shows that the nearest size is a No. 11 S.W.G., which has a section of 0.0105 square inch, or 13,200 circular mils. This has (at 60° C.) a resistance of 0.947 ohms per 1000 feet, and a weight of 41 lb. per 1000 feet. Now that 500 volts shall send 6 amperes implies a total resistance of  $500 \div 6 = 83.3$  ohms. The total length of shunt wire needed will therefore be  $83.3 \div 0.947$  or about 87 times 1000 feet, or 87,000 feet, weighing about 3567 lb.

In small machines the current density in the shunt-winding may safely exceed 1000 amperes per square inch, and even attain 1400. In the Scott and Mountain generators, p. 198, it varies from 660 to 1360.

*Given the ampere-turns, the volts, and the mean length of one turn to find the gauge of the wire, the resistance, the number of turns and the volume.*

This case derives its importance from its use in calculating *shunt windings*. Let the prescribed number of ampere-turns be called CS, neither C nor S being separately known. Let the volts applied to the terminals of the bobbin be V, and let M denote the mean length of one turn. (In many cases this will be only approximately known at first.) Let  $r_1$  stand for the resistance per inch length, and  $\rho_1$  the resistance (of the covered wire) per cubic inch. These last are supposed to be tabulated for various gauges. Now the resistance R of the coil may be expressed in two different ways:

$$R = \frac{V}{C} M r_1 S \quad . \quad . \quad . \quad (1)$$

and

$$M r_1 CS = V,$$

whence

$$\frac{V}{(CS) M} = r_1; \quad . \quad . \quad . \quad (2)$$

which fixes the gauge.

*Example.*—A shunt dynamo with 8 coils in series, working at 200 volts, requires 5200 ampere-turns of excitation per pole. The pole cores are circular of 10 inches diameter: the winding is expected to lie about 3 inches deep; whence internal diameter of windings will be about 11 inches, external about 16, so that the mean length of 1 turn will be about 42.5 inches. Then  $V = 25$ ;  $CS = 5200$ ;  $M = 42.5$ ; whence  $r_1 = 0.0001131$  ohms per inch. This is equal to 0.0013572 ohms per foot or 1.357 ohms per 1000 feet. Referring to the Wire-Gauge Table in the Appendix we observe that the nearest larger size is a No. 12 S.W.G., which (at 60° C.) has a resistance of 1.114 ohms per 1000 feet.

If a square wire is to be used, the area in square mils may be found by dividing 0.79 by the number of ohms per inch calculated as above.

The gauge having been found, let a suitable thickness of insulation be fixed upon and the resistance per cubic inch  $\rho_1$  be ascertained. It may be noted that *if square order of winding be assumed* then  $\rho_1 = \omega \div d_1^2$ ; where  $d_1$  is the diameter

of the covered wire in mils: but  $\rho_1$  is best taken from actual tables of windings that have been carried out. If  $\rho_1$  is thus known,  $\rho_1 \times \text{volume} = R$ . If the volume of the coil is given this settles the resistance,<sup>1</sup> and if  $R$  is thus ascertained dividing it by  $Mr_1$  gives the number of turns  $S$ . Or dividing  $R$  by  $r_1$  gives the total length required for the coil.

If the volume of the coil is not prescribed beforehand we must work from other data. Suppose the *number of watts that may be wasted in heating* is given. (This may be estimated (a) as a percentage of the whole output, see p. 117 or (b) from the estimated available cooling surface and the permissible rise of temperature, see p. 66.) Call the watts that will be wasted in heating the coil  $W$ . Then

$$W = VC = C^2R = V^2/R \quad . \quad . \quad (3)$$

$$\text{and as } R = \rho_1 \times \text{volume}$$

it follows that

$$\text{volume} = \frac{V^2}{\rho_1 W} = \frac{V}{\rho_1 C} \quad . \quad . \quad (4)$$

From this we see that the volume can be calculated if either the watts or the current are prescribed.

If the permissible temperature is also prescribed this (see p. 66) fixes the permissible number of watts per square inch of cooling surface; and this latter being settled, determines the number of square inches of surface that the coil must have. If the coil as designed proves to have an insufficient surface, then it must be re-designed so as to have a longer length, or else the volume of the whole must be increased, and a greater weight of copper used; and if new dimensions are thus chosen a new value must be taken of the mean length of one turn and the computation repeated.

It must be ever borne in mind that in shunt windings, if the mean length of one turn is prescribed, and a given number of ampere-turns is prescribed, everything depends upon the resistance per turn, and therefore *on the gauge*. Suppose a shunt winding to have 1000 turns, it will have a certain resist-

<sup>1</sup> See also formulæ by Löwit in *Elektrot. Zeitschr.*, xxi. 881, 1900.

ance, therefore at the prescribed voltage takes a certain current producing a definite number of ampere-turns. Now suppose that half the windings are cut out, while preserving the same mean length per turn. The remaining 500 turns will offer half the resistance, and will therefore receive twice as much current as before, bringing up the ampere-turns to the previous value; but the  $C^2R$  loss will have been doubled. Increasing the length of a shunt bobbin while preserving the same depth of winding and same gauge of wire, will therefore enable the required excitation to be obtained with a lessened waste of energy.

If the volts, heat loss, the watts per square inch, mean length of one turn, and resistance per cubic inch are all known the length  $L$  of the bobbin (in inches) can be found from the formula

$$L = \left( M \frac{W}{\xi} - \frac{\pi V^2}{\rho_1 W} \right) \div M^2; \quad (5)$$

where  $W$  is the number of watts of permissible heat loss, and  $\xi$  the permissible number of watts per square inch, dependent on the permissible temperature rise.

Another way of calculating the gauge of the wire from the ampere-turns, the volts, and the mean length of one turn is as follows:—Let  $k$  be the resistance of a wire 1 inch long and 1 mil in diameter, ( $= 0.9$  ohms at  $30^\circ \text{C}$ ), then

$$R = \frac{V}{C} = k \frac{SM}{d^2},$$

where  $d$  is the diameter in mils. We may deduce:—

$$d = \sqrt{\frac{kCSM}{V}}. \quad (6)$$

*Example.*—Taking, as in the former example,  $V=25$ ;  $CS=5200$ ;  $M=42.5$ ; and taking  $k=0.9$ , the formula gives  $d=89.2$  mils, which is between Nos. 13 and 14 S.W.G. If we had taken the temperature as  $50^\circ \text{C}$ ., we should have had  $k=0.972$ , and  $d=92$  mils, which is almost exactly No. 13 S.W.G.

If square order in the winding be assumed the number of

turns in one layer and number of layers, occupied by a coil of  $S$  turns of external diameter  $d_1$  mils, having a nett length of winding space  $L$  (inches), can be calculated from the following formulæ:

$$\begin{aligned}\text{No. of turns in 1 layer} &= 1000 L \div d_1. \\ \text{No. of layers} &= Sd_1 \div 1000 L.\end{aligned}$$

Hence the radial depth or thickness  $T$  of the coil would be

$$T = Sd_1 \div 1,000,000 L;$$

but owing to bedding,  $T$  will probably come a little less than this. Further, it is not safe to assume without trial that the number of turns in one layer can be found by the formula from a measurement of  $d_1$  made with callipers. The right way is to try by winding a piece of coil with the wire in question. A few turns may be wound on a wooden core and the length occupied by 10 turns should be accurately measured, and divided by 10 to find the working value of  $d_1$ .

Curves to facilitate calculations for magnet winding have been given by Mr. H. H. Wood in the *Electrical World*, xxv, pp. 503 and 529, April 1895.

The following rules, due to Mr. Kapp, give the *weights* of copper in coils,  $W$  standing for the permissible number of watts wasted,  $D$  the mean diameter in inches,  $M$  the mean length of one turn in inches (for coils not circular in shape), and  $CS$  stands for the prescribed number of ampere-turns of excitation.

$$\text{weight in lbs.} = 2.4 \times 10^{-6} \times \frac{(CS)^2 D^2}{W}; \quad (7)$$

$$\text{weight in lbs.} = 0.245 \times 10^{-6} \times \frac{(CS)^2 M^2}{W} \quad (8)$$

#### COIL WINDING.

Coils for field-magnets may be classified as (a) *bobbin-wound*, (b) *former-wound*. In those wound on bobbins no special instructions are needed, except as to modes of fixing and bringing out the ends. Square wire is preferable in every

case where the wire is to be wound to a radial depth exceeding one inch, as it gives a much better space-factor than round wire. Better still is edge-strip winding where it can be used.

*Field-magnet Bobbins.*—These are made variously of brass with brass flanges, of sheet iron with brass flanges, of very thin cast iron, sometimes even of zinc. Some makers use sheet metal with a flange of hardwood, such as teak. The reader should examine the examples given in the following pages: in particular the Scott and Mountain machine, page 160, Plate II.; the Kolben machine, page 216, Plate VII.; and the English Electric Manufacturing Co.'s machine, page 222. Ample pains must be taken to line the bobbin with adequate insulating materials such as layers of press-spahn, vulcanized fibre, or varnished mill-board. Great attention must be paid to the manner of bringing out and securing the inner end of the coil. If a bobbin is simply put upon a lathe to be wound, the inner end of the wire, which must be properly secured, requires to be brought out in such a way that it cannot possibly make a short-circuit with any of the wires in the upper layers as they cross it. A method of winding which obviates all difficulty on this score is to wind the coil in two separate halves, the two inner ends of which are united, so that both the working ends of the coil come to the outside. Fig. 14 shows such a bobbin. The windings are secured by bindings of tape. This



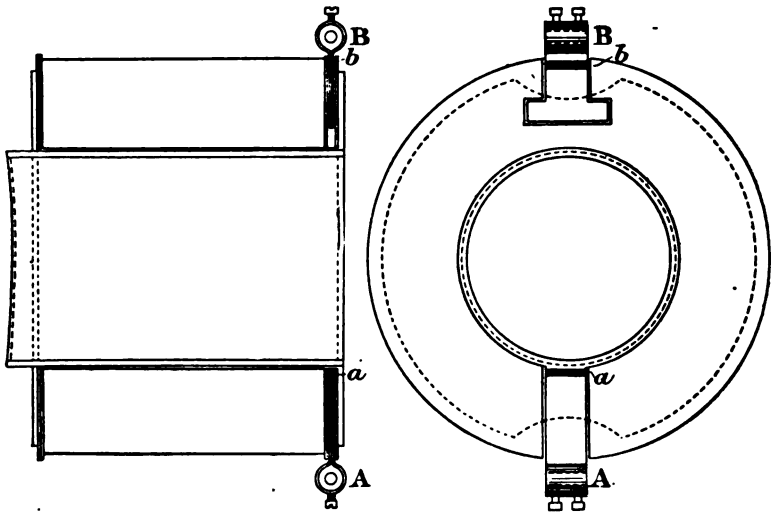
FIG. 14.—BOBBIN WITH BOTH ENDS AT OUTSIDE.



FIG. 15.—STRIP-WOUND COIL.

method of construction has been used for years in winding the secondaries of induction coils, where it is desirable to keep the ends of the winding away from the iron core and from the

tect the joint between the cylindrical part and the flanges. As an example of careful insulation, may be cited the method adopted at Schenectady for insulating the magnets of the Edison bipolar machines, working at 100 to 125 volts, which are



FIGS. 19 AND 20.—METHOD OF BRINGING OUT ENDS.

insulated as follows: End-rings of hard rubber are wedged upon the iron cores with mica. When bits of sheet mica are used, these are cut to be  $1\frac{1}{2}$  inch wide and at least 3 inches long; but when "made mica" sheets are used, long strips 5 inches wide are cut, and conformed by heating to the curvature of the core. In either case the mica projects at least 1 inch on the



FIG. 21.—COIL TERMINAL PIECE.

inner side of the ring. Then over the core is laid one layer of varnished muslin 24 mils thick, cut to the exact width between the end-rings. Upon this are placed two layers of plain pressed board 20 mils thick, cut one inch wider than the width be-

internally while they are being baked. They thus become thoroughly mummified and hard. For such motors an asbestos insulation is sometimes prescribed. All field-magnet coils, whether bobbin-wound or former-wound, ought indeed to be thoroughly soaked with varnish and stove-baked.

*Bringing out and fixing of Ends.*—Figs. 18 to 20 illustrate methods used for bringing out the ends of coils. In Fig. 18 copper strip, laid in behind an end-sheet of insulating material, makes connexion to the inner end, as shown in the upper side of the figure, while another strip, shown in the under side similarly inlaid, serves as a mechanical as well as an electrical attachment for the outer end of the winding. This device is due to Mr. Kapp.

Another method, due to Messrs. Ganz and Co., is illustrated in Figs. 19 and 20.

A simple device for securing the outer end is to fashion a terminal piece like Fig. 21 so that it can be laid upon the windings, the last three or four turns of which are wound over its base, and after winding are bared at the place and soldered securely upon it.

*Insulation of Field-Magnet Coils.*—It is not absolutely

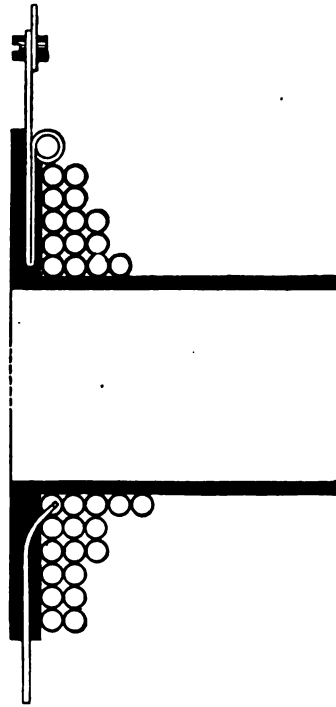


FIG. 18.—MODE OF BRINGING OUT ENDS.

necessary to use any mica preparation for insulation of field-magnet bobbins, several layers of paper preparations being more often used. One tenth of an inch thickness, if made up of several superposed layers, is generally adequate. Varnished canvas is useful as an underlay, and press-spahn or vulcanized fibre for lining the flanges. It is important to pro-

magnet frame are more efficacious than the external surface of the coil in dissipating the heat.

Some considerations in general concerning the heating of coils may here be discussed. If it be assumed that the thickness of the insulation is proportional to the thickness of the wire upon which it is wound, it follows that the weight of copper in a coil filling a bobbin of even dimensions will be the same, whether a thick wire or a thin one be used. Further, for a given volume to be filled with coils, the resistance in ohms of the coil will vary directly as the square of the number of turns in the coil. For if a coil wound with 100 turns of a given gauge be rewound with 200 turns of a wire having half the sectional area, the resistance of the new winding will obviously be four times as great as that of the original winding. Also by a similar argument, it follows that the resistance of a coil of given volume will vary *inversely as the square of the sectional area* of the wire used. And as the area is proportional to the square of the diameter of the wire, it follows that the resistance is *inversely proportional to the fourth power of the diameter* of the wire used.

The amount of heat developed per second in a coil is the product of the resistance into the square of the strength of the current. To avoid waste, therefore, no unnecessary resistance should be introduced into any main-circuit coil. It is easy to show that with a coil of *given volume*, the heat-waste is the same for the same magnetizing power, no matter whether the coil consists of few windings of thick wire or many windings of thin wire. The heat per second is  $C^2 R_m$ , and the magnetizing power is  $S C$ ;  $C$  being the current,  $R_m$  the resistance, and  $S$  the number of turns. But  $R_m$  varies as the square of  $S$ , if the volume occupied by the coils is constant. For suppose we double the number of coils, and halve the cross-sectional area of the wire, each foot of the thinner wire will offer twice as much resistance as before; and there are twice as many feet of wire. The resistance is quadrupled therefore. The heat is then proportional to  $C^2 S^2$ : and therefore the heat is proportional to the square of the magnetizing power. If, therefore, we apply the same magnetizing power by means

of the coil, the heat-waste is the same, however the coil is wound. To magnetize the field-magnets of a dynamo to the same degree of intensity requires the same expenditure of electric energy, whether they are series wound or shunt wound, *provided the volume is the same, and the space factor is unaltered*. Any increase in the space-factor is equivalent to a larger volume, or to the discovery of a wire having a lower specific resistance. With a higher space-factor the prescribed excitation can be attained with a lesser waste of energy. This is the reason for the advantage of using square wire or strip winding instead of round wire.

A simple way of looking at this matter is to regard the whole winding as consisting of one turn, there being a current, equal to the total ampere-turns, going only once round. Then this current divided by the total cross section of copper gives the current-density. We then see that for equal-sized bobbins (containing the same amount of copper) the magnetizing effect is simply proportional to the current density. Further, the power wasted per lb. of copper is proportional to the square of the current-density. The following Table VII. gives the waste in watts for different current-densities in both inch and centimetre measure. The temperature of the coil is taken at 30° C., at which temperature the resistance of an inch cube of copper may be taken at  $0.7 \times 10^{-6}$  ohm.

If the *volume* of the coil (and the weight of copper in it) may be increased, then the heat-waste for a given magnetizing force may be proportionally lessened. For example, suppose a shunt-coil of resistance  $r$  has  $S$  turns; if we wind on another  $S$  turns in addition, the magnetizing power will remain nearly the same, though the current will be cut down to one-half owing to the doubling of the resistance; and the heat-loss will be halved, for  $2 R_{\text{w}} \times (\frac{1}{2} C)^2$  will be  $\frac{1}{2} C^2 R_{\text{w}}$ .

It is assumed in the foregoing argument that we get double the number of turns on if we halve the sectional area of the copper wire. This is not quite true, because the thickness of the insulating covering bears a greater ratio to the diameter of the wire for wires of small gauge than for wires of large gauge. In designing dynamos, moreover, one ought to be

guided by the question of economy, not by the accident of there being only a certain volume left for winding. If there is insufficient space round the cores to wind on the amount of wire that economy dictates, new cores should be designed, having a sufficient length to receive the wire which is economically appropriate.

TABLE VII.—LOSS OF POWER IN COPPER CONDUCTORS AT DIFFERENT CURRENT-DENSITIES.

Current-Density.		Watts converted into Heat.		
Amperes per sq. in.	Amperes per sq. cm.	Per cubic in. of copper.	Per cubic cm. of copper.	Per lb. of copper.
400	62	0·112	0·0068	0·548
500	77·5	0·175	0·0106	0·544
600	93	0·252	0·0154	0·784
700	108·5	0·340	0·0204	1·057
800	124	0·448	0·0273	1·393
900	139·5	0·567	0·0340	1·758
1000	155	0·7	0·042	2·17
1500	232	1·57	0·096	4·88
2000	310	2·8	0·171	8·71
2500	387	4·37	0·266	13·59
3000	465	6·3	0·384	19·59
3500	542	8·5	0·510	26·43
4000	620	11·2	0·683	34·83

In order then that any coil (whether upon the armature or field-system) may not overheat, it must have sufficient surface relatively to the amount of heat developed in it by the current. For equal watt loss per unit area of radiating surface, the amount of heat developed will be entirely different in field-magnets and armatures, on account of the different conditions under which the heat is liberated, and consequently we must consider them separately.

*Heating of Field-Magnets and Stationary Bobbins generally.*

Let  $w_m$  be the total watts wasted in the field-coils at full load, that is  $w_m = (C_M^2 R_M + C^2 R_s)$

$A_1$  be the total heat-radiating area of all the bobbins, in square inches, not counting end flanges and internal surfaces (if any.)

$\theta_m$  represent the final temperature rise above the surrounding air.

Then

$$\theta_m \propto w_m,$$

and

$$\theta_m \propto \frac{1}{A_1};$$

or

$$\theta_m = \frac{w_m}{A_1} \times h.$$

The value of the constant  $h$  depends upon the depth of winding, upon the amount of the draught set up by the fanning action of the armature, and upon the condition of the air, that is, circulating or still. According to Mr. W. B. Esson, the value  $h$  may be taken as 55 for ordinary field bobbins. That is to say an emission of wasted heat at the rate of 1 watt per square inch will cause a rise of  $55^\circ$  C.; or, if  $30^\circ$  C. be taken as the permissible amount of rise, the coil must expose  $1.83$  square inches per watt wasted in it. This figure appears to be low for modern machines. The temperature is here assumed to be measured by thermometer at the surface of the coil, covered with a pad of cotton-wool. For the usual shape and dimensions of field bobbins, more particularly those of multipolar machines other than iron-clad types, the formula

$$\theta_m(\text{in Centigrade degrees}) = \frac{w_m}{A_1} \times 75 \quad (9)$$

will be found to give good results. The value of the heating constant is higher for iron-clad types and enclosed motors.

For shunt bobbins this formula gives directly the maxi-

mum shunt current  $C_m$  that may be used if the temperature rise is prescribed as a limit. Thus

$$w_m = V \times C_m = C_m^2 R_m$$

$$C_m = \sqrt{\frac{\theta_m \times A_1}{75 \times R_m}}. \quad \dots \quad (10)$$

Or, if the excitation watts and temperature rise are given we have for the necessary radiating surface of the coils

$$A_1 = \frac{75 \times w_m}{\theta}. \quad \dots \quad (11)$$

In the case of *edge-strip coils* being used, the temperature rise will be much less than that calculated by these formulæ, because in coils of this species the internally-generated heat is conducted much better to the surface, whence it escapes without the internal temperature rising so high. Messrs. Ferranti found the temperature rise after 6 hours in a 1500 kilowatt machine at 150 revs. per min. to be only 16 deg. C. though the current-density was 920 amps. per sq. inch. In a 150 kilowatt machine at 380 revs. per min., and 1200 amps. per sq. inch, the temperature rise was only 14.5 deg. C. after 6 hours. In one case where an edge-strip winding was in two layers with insulation between, though the current-density was only 800 amps. per sq. inch, the rise was about 28 deg. C. after a 5 hours' run.

At the Oerlikon Works, a limit of 30 deg. C. assigned to the heating of a stationary bobbin, is found to correspond to an emission of 0.4515 watts per square inch: or 2.2 square inches of radiating surface are necessary for getting rid of each watt wasted in heating. This makes the constant  $h = 66$ .

If we assume that a limit of temperature rise of 50 deg. C. above that of the surrounding air is safe, then the largest current which may be used with a given stationary magnet coil, is expressed by the formula:—

$$\text{maximum permissible current} = 0.95 \sqrt{\frac{A}{R_m}}.$$

Similarly, for *shunt coils* we have

$$\text{maximum permissible voltage} = 0.95 \sqrt{AR_m}.$$

Some recent measurements of the rise and distribution of temperature in field-magnet coils have been made by E. Brown,<sup>1</sup> and by Neu, Levine and Havill.<sup>2</sup> Brown's observation made on a bipolar Siemens dynamo led him to note how efficacious in promoting cooling was the metal in proximity. He recommended that the bobbin-heads should be made as good conductors of heat as possible; that any gap between the pole-core and the bobbins should, if possible, be filled up with good conducting material; and that, as bobbins heat most at the mid-length they should be made of less depth there, that is of an hour-glass form. The Electric Construction Company undulates (see Fig. 92) the profile of its field-coils for the purpose of better cooling. Messrs. Neu, Levine, and Havill, using a bipolar Crocker-Wheeler motor, explored the distribution of temperature throughout the cross-section of the coils, by electrical measurement of the rise of resistance of the various parts of the winding, and also measured the apparent rise of temperature with thermometers. They plotted isothermal curves showing how under varying conditions the temperature is distributed, when the coil was, (1) supported in the air, (2) standing on a table, (3) in place on the machine at rest, (4) in place on the machine running at full load; in each case the coil being heated for six hours at the rated voltage. The first case showed the greatest heating, for, though the table arrested the circulation of air, it seemed to cool the whole coil. The average rise in the four cases was 37·5, 33·9, 22·7 and 28·3 deg. C. respectively. In case 3 the iron core conducted away more heat than the external air, the point of maximum temperature being nearer to the surface than to the core. They observed on the machine running at full load, a rise of 110 deg. C. *per watt per square inch of exposed cylindrical coil surface*; or on, the machine stationary, a rise of 100 deg. C. This makes the formula:—

$$\theta_m \text{ (in Centigrade degrees)} = \frac{W_m}{A_{cyl}} \times 110 \quad (12)$$

<sup>1</sup> *Journal of the Inst. of Elec. Engineers*, vol. xxx. page 1159, 1901.

<sup>2</sup> *Electrical World*, vol. xxxviii. page 56, July 13, 1901.

leading to the result that if the limit of rise be set at 30 deg. C. there must be allowed no less than 3·66 inches of cylindrical per watt wasted in the magnet coil. It appeared that a surface exposed to contact with iron was nearly twice as efficacious as a surface exposed to air, leading to the rule :—

$$\theta_m \text{ (in Centigrade degrees)} = 340 \frac{W_m}{A_a + 1.875A_i} \quad (13)$$

where  $A_a$  is the area exposed to air and  $A_i$  that in contact with iron.

They found the true mean rise of temperature as measured by increase of resistance to be 1·4 to 1·6 or more times as great as the apparent mean rise measured by thermometer.

In the case of enclosed motors, without any resort to artificial cooling, it is difficult to prevent the internal temperature from rising by as much as 100 deg. C. above that of the surrounding air. Some makers provide their enclosed motors with external radiating ribs to aid dissipation of the heat. For these the temperature-rise (according to Niethammer) may be reckoned as equal to about 95 to 140 times the total watts lost divided by the *total* surface, in square inches, that is exposed to the circulation of air.

*Heating of Armatures or Running Coils.*—The amount of heat liberated in a rotating armature depends principally upon :—

(1) The heat radiating surface  $A_2$ . In estimating this, the number of square inches exposed to the cooling action of the air are to be taken, but it is a matter of discretion to estimate what proportion of the internal surfaces contribute to it.

(2) The peripheral speed  $v$  of the winding. For small armatures and ring winding the average peripheral speed (feet per minute) as given by the average diameter of the armature, is to be taken.

(3) The proportion, within limits, of radiating surface to polar surface. Naturally, an armature nearly covered by the pole-pieces will not have, as a rule, such a good chance of

getting rid of the developed heat, as one whose radiating surface is more open to the air.

The heating of an armature in which  $w_a$  total watts (iron and copper losses) are being wasted can be estimated from the formula

$$\theta_a = \frac{w_a}{A_s} \times \frac{a}{1 + (b \times v)} \quad \cdot \quad \cdot \quad \cdot \quad (14)$$

where  $a$  and  $b$  are constants—the values of which are dependent on the type of machine.

The constant  $a$  varies in ordinary well-ventilated machines of modern design from 50 to 90, while constant  $b$  appears to vary from 0.0004 to 0.0009, if  $v$  is in feet per minute. The curves given in Fig. 22 are, however, more convenient to employ for estimating the temperature rise, as representing what is usually found in modern practice. The ordinates represent the rise of temperature per watt per square inch and the abscissæ the peripheral speeds. Curve A A is to be used for small unventilated armatures, and is based upon the average results of Messrs. A. H. and C. E. Timmermann,<sup>1</sup> and with tests made upon actual machines. Curves B B and C C are to be used for estimating the temperature rise of small well-ventilated armatures and large ventilated armatures more or less of a fly-wheel nature, respectively.

Hence to find the temperature rise  $\theta_a$  of any armature running at a peripheral speed of  $v$  feet per minute: Divide the number of watts wasted by the number of square inches, and then from one or other of the curves find the temperature rise corresponding at the peripheral speed in question.

At the Oerlikon Works, it was found that, taking a surface speed of about 2000 feet per minute, each square inch of armature surface (external), and a permissible temperature rise of 30° C., each square inch could dissipate from 1.29 to 1.61 watts; or each watt requires from 0.6 to 0.8 square inch. Assuming 4 per cent. of the output to be wasted in armature heat, or 40 watts per kilowatt, the necessary armature surface must therefore be about 24 to 32 square inches per kilowatt of output.

<sup>1</sup> *Trans. Amer. Inst. Electr. Engineers*, x. 1893.

Owing to the cooling effect of the air-currents when the armature is running it is found that when a dynamo is stopped at the end of a long run, the surface temperature immediately rises above what it was when the machine was running, as the heat which is being conducted outwards from the hotter interior is not now so rapidly got rid of. Thus we find that in Admiralty specifications it is laid down that after the end of a run

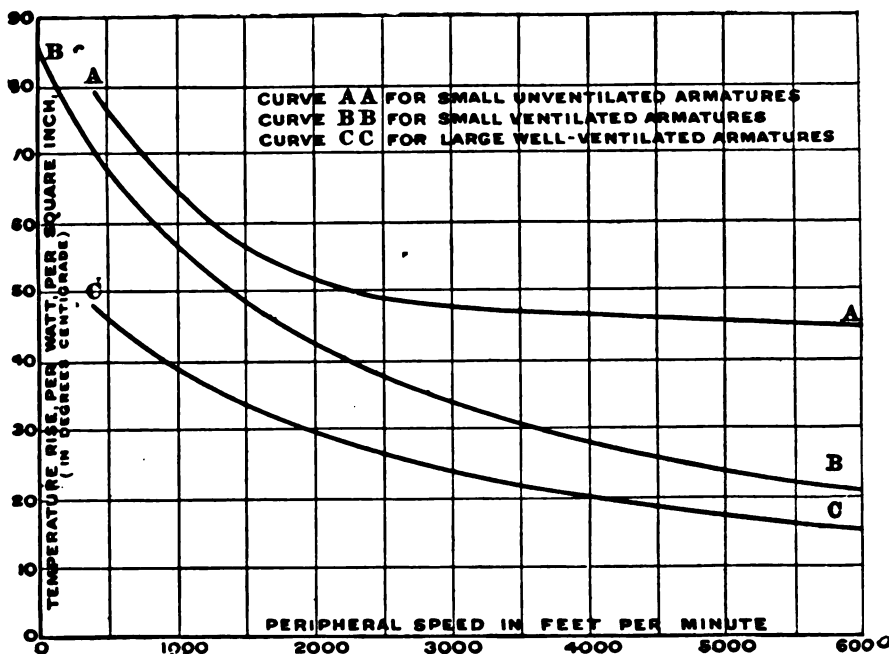


FIG. 22.—CURVES FOR ESTIMATING TEMPERATURE RISE.

of six hours at full-load, no part of the machine shall at the end of one minute after stopping show a greater rise than  $30^{\circ}$  F. ( $=16.6^{\circ}$  C.) above the surrounding air. This does not by any means imply the final temperature rise, because the thermometer will invariably continue to rise for a much longer period than one minute. But in any case this temperature limit is needlessly low, as a rise of twice as much would be perfectly safe, even in the hottest engine-room.

## CHAPTER IV.

## INSULATING MATERIALS AND THEIR PROPERTIES.

INSULATING MATERIALS may be classified under several heads:—

- (i.) *Vitreous*, including glass, “vitrite,” and sundry kinds of slags.
- (ii.) *Stony*, such as slate, marble, steatite, mica, asbestos, kieselguhr, stone-ware, porcelain, “petrificate.”
- (iii.) *Osseous*, such as bone and ivory.
- (iv.) *Resinous*, including shellac, resins of all sorts, copal and other gums.
- (v.) *Bituminous*, as bitumen, asphaltum, pitch.
- (vi.) *Waxy*, including bees-wax, solid paraffin, ozokerit, and the like.
- (vii.) *Elastic*, such as indiarubber, natural and vulcanized, ebonite, gutta-percha.
- (viii.) *Oily*, including various oils and fats of animal and vegetable origin, as well as mineral petroleum.
- (ix.) *Cellulose*, including dry wood and paper; many natural substances, such as bamboo, wood pulp, and many preparations of paper and of wood pulp, papier-mâché, press-spahn, manila-paper, vegetable parchment, “vulcanized fibre,” celluloid, “Willesden paper.”
- (x.) *Silk*, and allied animal tissues such as cat-gut.
- (xi.) *Sulphur*.

From these materials, or some of them, there are now manufactured a number of artificial preparations known under trade names, such as “ambroin,” “megohmite,” “stabilite,” “micanite,” “vulcabeston,” oiled-paper, “empire cloth,” insu-

lating tape, and kindred fabrics; also special varnishes such as "armalac," "japan," "enamelac," "Sterling's varnish," and "Scott's rubber varnish."

*Dielectric Resistance.*—All insulating materials are mechanically bad. They differ enormously in their specific electric resistance, and in their power of resisting penetration by a spark. They all share the particular property that as their temperature is raised their electric resistance decreases enormously, and in general they become fairly good conductors so soon as any chemical change begins. Even marble, glass, and porcelain begin to conduct as electrolytes below a red heat. Some are liable to absorb moisture from the atmosphere and so lose their insulating properties.

The most important thing to know about such insulating materials as are used in dynamo construction is their power to resist being pierced by a spark. It is also important to know whether they are hygroscopic, whether they are impaired when their temperature is raised, and whether they deteriorate with time.

Porcelain and stoneware are used for insulating bushes, and as supports for terminals. Dry wood and paper preparations such as press-spahn, vulcanised fibre, paper-mâché, oiled canvas and the like are only used for low voltages, or as secondary insulators, that is insulators which, while mechanically holding the conducting parts apart, form a backing for some better primary insulator such as mica.

Experimental data as to the dielectric strength of insulating materials have been made from time to time by various authorities. From these the following have been collected. Fig. 23 relates to layers of *pure mica* and of *oiled canvas* of different thicknesses, and to the number of volts required to break them down. The experiments, which were made at the Oerlikon works, consisted in putting layers of the substances between the electrodes, and gradually increasing the voltage until the substance began to heat up between the poles.

Fig. 24 relates to *micanite*, that is to say to thin laminæ of mica cemented together with a special gum such as pure

shellac. It is found that when a sheet of micanite is placed between two electrodes, and the voltage is gradually raised, a point is reached when, with a sheet of given thickness, a current begins to flow through the micanite, heating it up within, and producing a burning which rapidly destroys the insulation. Micanite is a good insulator even at  $150^{\circ}\text{C.}$ , and its break-down when the limiting voltage is reached, appears to be due to the chemical decomposition, not of the mica, but

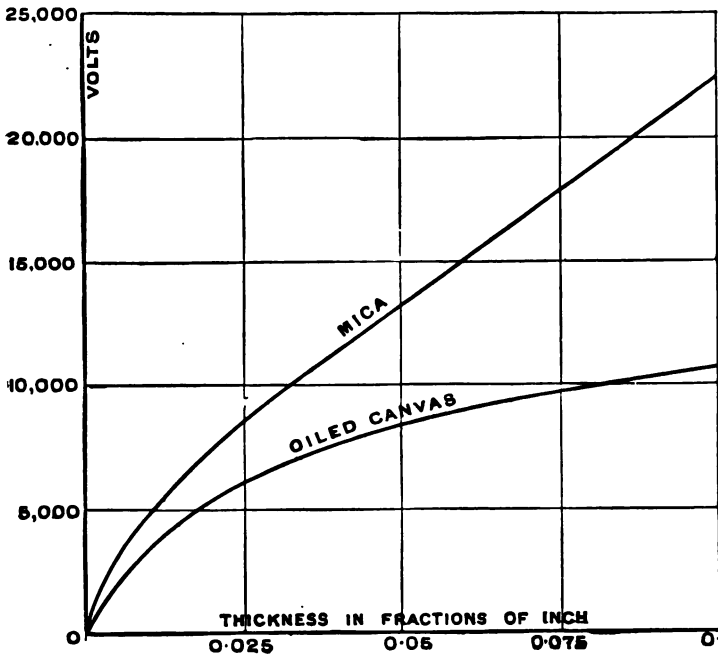


FIG. 23.—CURVES OF DIELECTRIC STRENGTH.

of the cementing varnish. Pure mica in sheets, whether of white or of brownish or greenish tint, if clear has an enormous power of resisting puncture by the spark, some samples withstanding as much as 5000 or more volts per mil thickness. Mica-canvas consists of mica scrap sheets about 2 mils thick, and overlapping one another, cemented with shellac varnish between two sheets of canvas; the total thickness being about 50 mils and withstanding 3000 volts (alternating). Mica long-

cloth consists of mica scraps similarly cemented between a very thin "linen" fabric; its thickness being about 25 mils. In making each of these compositions the sheets are baked for at least twenty-four hours in a steam-heated oven.

The data given in the following table are only very approximate, as in most cases the compositions vary somewhat, and differ at different temperatures. Taking these figures as being true at ordinary temperature of the air, it is probable

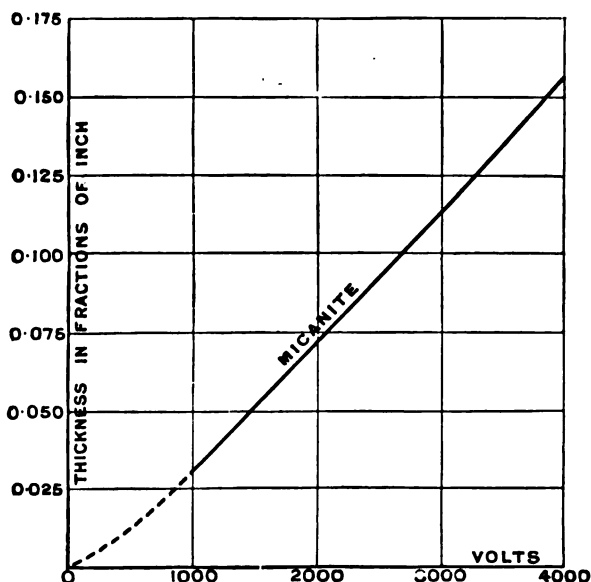


FIG. 24.—INSULATION VOLTAGE OF MICANITE.

that in most cases a rise of 30 deg. Centig. would reduce them to half their value, pure mica being less affected, and paraffined paper much more affected than the rest of those mentioned.

A discrepancy appears between the figures for mica in this table (800 to 8000 volts per mil), and the Oerlikon figures (about 22 volts per mil). The Oerlikon figures relate to the production of the *heating* which indicates incipient breakdown, while the figures in the table relate to *piercing* by a

sudden spark. Many makers allow, as a safe insulation, 1 millimetre per 500 volts, which is about 12 volts per mil.

Hobart using a mixed insulation allows the following thicknesses in armature slots: 1·2 mm. for 115 volt machines, 1·3 mm. for 230 volts, 1·5 mm. for 550 volts; the guaranteed insulation test from copper to iron at 20° C. being from 2500 to 3500 alternating volts applied for one minute.

TABLE VIII.

Material.	Dielectric Strength (volts per mil)	Megohms per mil thickness, for 1 sq. inch.	Remarks.
Mica, clear flat . . .	800-5000	30,000	varying in quality.
Micanite plate . . .	900-1200	1,000,000	
Mica canvas . . . .	60-70	300,000	
Mica long cloth . . .	60-70	300,000	
Mica paper, flexible .	300-800	300,000	
Press spahn. . . . .	300-400	100	hygroscopic.
Paraffined paper . . .	800-1000	10,000,000	softens when warm.
Oiled paper . . . . .	500-900	1350	{ made with pure boiled linseed oil.
Shellacked paper . . .	50-125	20	cartridge paper.
Manila paper . . . . .	120	4	dried, unvarnished.
Double cotton, shellacked	250-300	25	as on D.C.C. wires.
Hard rubber . . . . .	500-1200	600	varies much with quality
Vulcanized fibre . . .	120-200	400	hygroscopic.
Thinnest insulating tape	150	20	thickness about 7 mils.
Vulcabeston . . . . .	20	15	
Dry mahogany or maple	15	0·5	
Slate . . . . .	5	0·5	{ ought to be boiled in paraffin

Dry wood is used in armature construction as a packing under windings to prevent abrasion where they turn through a sudden curve. Slate is only used for terminal boards, and must be free from metallic veins. Vulcabeston, consisting essentially of asbestos cemented together with a small quantity of rubber and vulcanized, is useful as being capable of

being moulded: it does not lose its insulating properties if heated even to 300° C. Stabilit, which is manufactured in sheets and tubes, is said to withstand 10,000 or 15,000 volts with a thickness of 1 millimetre or about 400 to 600 volts per mil. It is non-hygroscopic and can be moulded. The measured resistance is about 40,000 ohms per mil thickness. Megohmite is a mica composition also capable of being moulded. All paraffined compositions have a very high apparent insulation resistance, but are quite unsuitable if the temperature rises so little as 30 deg. Centig. Cardboard baked and then while hot impregnated with shellac or other insulating varnish makes an excellent material for lining armature slots. Another paper preparation is known as "Carton Lyon." For all voltages over 500, an insulation containing mica is to be preferred, and indeed is indispensable for all high-voltage work.

There is a serious objection to resin, shellac, and to varnishes containing shellac and resin, that these substances when heated give off vegetable acids which in time corrode the copper. Hence other varnishes have been sought which are not open to this objection. Among these are "Sterling varnish" and "enamellac."

The Pittsburg Insulating Company manufactures various fabrics and papers impregnated with "Sterling varnish" and is responsible for the following particulars:—

TABLE IX.

Material.	Grade.	Thickness in mils.	Puncture Test in volts.	Guaranteed resist- ance to puncture.
Bond paper . . .	A	4- 5	5,000- 9,000	..
Fibre paper . . .	A	6- 7	8,000-10,000	..
Red rope paper .	A	9-10	9,000-11,000	..
Paper . . . .	A	6- 7	8,000-10,000	..
Paper . . . .	B	9-10	14,000-16,000	10,000 volts
Paper . . . .	C	12-14	20,000-25,000	15,000 "
Linen . . . .	A	6- 7	5,000- 9,000	..
Linen . . . .	B	10-11	13,000-15,000	10,000 "
Linen . . . .	C	15-16	18,000-20,000	15,000 "

Sulphur mixed while melted with powdered glass, or with kieselguhr, forms a composition that can be poured into sockets or cavities and is an insulator.

*Insulation of Core-Bodies.*—After a core-body has been assembled and properly clamped upon its spider, it must be protected by insulation, so as to diminish any risk of making short-circuit with any of the conductors. Although these are each separately insulated, insulation of the core-body is also necessary as a double protection. Smooth cores are insulated over the cylindrical surface as well as at the ends. Toothed cores are insulated along the slots, as well as at the ends. Core-bodies for ring-wound armatures must also be insulated along the inner periphery of the core. "Empire cloth" is found very suitable for covering smooth cores.

*Insulation of Slots.*—It is usual to line the interiors of slots with a layer of insulating material, "Empire paper" is suitable as a first lining. For machines working at 500 volts or under, a lining of varnished paper or cardboard, 20 mils thick, is considered adequate, provided the individual conductors or the groups of conductors are themselves strongly insulated with micanite of 40 mils or 50 mils thickness. Sometimes a lining of mica-paper is used. For still higher voltages, micanite linings made of sheet-micanite are used. In the case of tunnel slots, or slots that are nearly closed between T-shaped teeth, micanite tubes are preferred. These, indeed, are general in the case of high-voltage alternating generators and motors.

For further and more detailed information the reader is referred to the following sources:—

*C. P. Steinmetz.*—Note on the disruptive Strength of Dielectrics. *Trans. Amer. Inst. Elec. Engineers*, x. 85, Feb. 21, 1893.

*Oerlikon Maschinen Fabrik.*—Sur le Calcul de Machines électriques, June 1900.

*Sever, Monell and Perry.*—Effect of Temperature on Insulating Materials. *Trans. Amer. Inst. Engineers*, xiii. 225, May 20, 1895.

*Parshall and Hobart.*—Electric Generators (1900).

*Canfield and Robinson.*—The Disruptive Strength of Insulating Materials, *Electrical Engineer* (N. Y.), xvii. 277, March 28, 1894.

## CHAPTER V.

## ARMATURE WINDING SCHEMES.

ARMATURE WINDINGS for continuous current generators and motors may be classified under two heads:—

1. *Parallel Grouping.*

- (a) Lap-windings (drum or barrel-winding).
- (b) Ring-windings.

2. *Series and Series-Parallel Grouping.*

- (a) Wave-windings (drum or barrel-winding).
- (b) Series ring-windings.

A mixed lap and wave-winding is sometimes used for grouping former-wound coils.

For a machine of prescribed speed and voltage the number of armature conductors necessary to produce the given voltage will depend not only on the number of poles and on the magnetic flux per pole, but on the grouping adopted for the conductors. The formulæ connecting these quantities are as follows, the symbols used having the following meanings:

$E$  = the prescribed number of volts to be generated.

$n$  = number of revolutions *per second*.

$p$  = the number of poles.

$c$  = the number of circuits or paths that are in parallel through the armature from brush to brush.

$C_a$  = the whole current carried by the armature.

$Z$  = the whole number of conductors carried in the slots of the armature.

$K$  = the number of segments in the commutator.

$N$  = the magnetic flux per pole, meaning the total number of magnetic lines that reach the armature from one pole.

The current in any one conductor will obviously be equal to  $C_a \div c$ .

The general formula then is

$$E = n \times Z \times N \times \frac{p}{c} \div 10^8 \quad . \quad . \quad . \quad (1)$$

whence

$$Z = \frac{c \times E}{n \times p \times N} \times 10^8 \quad . \quad . \quad . \quad (2)$$

In ordinary parallel groupings (lap-wound drum-armatures and ring-armatures)  $c = p$ , so that for these the formula (2) is simplified down to

$$Z = \frac{E \times 10^8}{n N} \quad . \quad . \quad . \quad (2a)$$

*Examples.*—(1) In a parallel-wound armature of a 12-pole tramway generator of the English Electric Manufacturing Co. (MP 12—1100—100);  $E = 550$ ;  $n = 1.666$ ;  $N = 25,647,000$ ;  $p = 12$ ;  $c = 12$ ; hence by formula (2) or (2a)  $Z = 1248$ .

(2) In the series-parallel armature of the 10-pole tramway generator of Kolben and Co., p. 216 (MP 10—250—125);  $E = 550$ ;  $n = 2.083$ ;  $N = 12,110,000$ ;  $p = 10$ ;  $c = 4$ ; hence by formula (2)  $Z = 874$ .

(3) In the series-parallel armature of the 12-pole tramway generator of the Oerlikon Co., p. 188 (MP 12—500—100);  $E = 550$ ;  $n = 1.666$ ;  $Z = 1326$ ;  $p = 12$ ;  $c = 6$ ; hence by formula (1)  $N = 12,445,000$ .

*Radial Diagrams.*—Figs. 25 and 26 are radial diagrams in which the conductors of the armature are represented by short radial lines, while the end-connectors are represented by curves or zigzags, those at one end of the armature being drawn within, those at the other end being drawn without the periphery. With such diagrams it is easier to follow the circuits and to distinguish the back and front pitches of the winding. The arrows show the direction of the induced electromotive-forces.

In Figs. 25 and 26 the armatures are supposed to be rotating in a 4-pole field.

Fig. 25 is a diagram of a lap-winding and Fig. 26 a wave-winding. It will be seen that while the lap-winding gives four circuits in parallel, the wave-winding gives but two circuits. It is a series-winding and gives with the same number of conductors double the electromotive-force; but, as the maximum

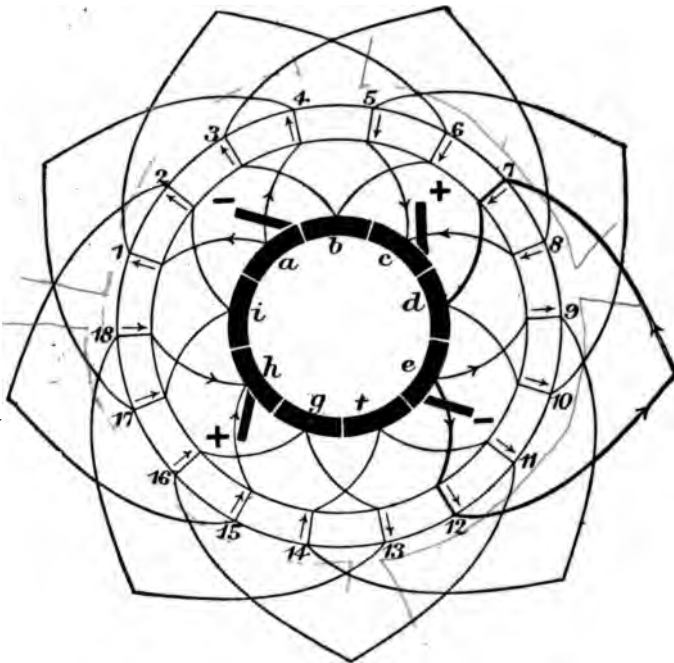


FIG. 25.—LAP-WINDING 4-POLE DRUM.

conductance of any one conductor is alike for the two machines, the series-winding, with only two circuits instead of four, will only yield half the currents.

*Field-Step.*—It will be noted that whereas in ordinary ring-windings and in lap-windings the winding at the completion of each element comes back to a point close to that from which it started, and therefore in the *same polar region*, the wave-windings all step forward to the *next polar region* of

the same name. There is no abstract reason why windings should not be imagined in which the step so made from one element of the winding to the next should not be to the region of a still more distant pole. Let  $m$  denote the number of such complete pole-pitches over which the step is made. Then, in general, we have for lap-windings  $m = 0$ ; for wave-windings  $m = 1$ ; and for ring-winding  $m = 0$  for parallel group-

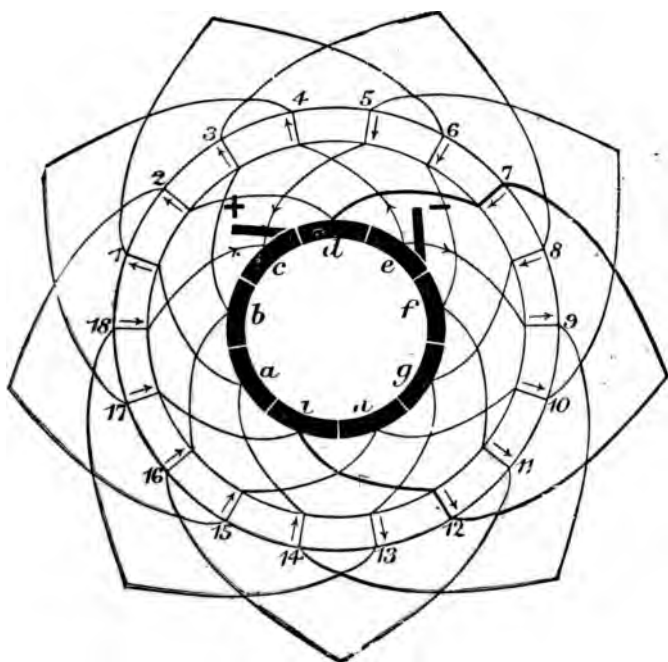


FIG. 26.—WAVE-WINDING 4-POLE DRUM.

ing, or  $m = 1$  for series grouping. The cases where  $m > 1$  are not practical.

*Groups of Conductors.*—Suppose an armature to have  $Z$  conductors arrayed in simple “elements” (either lap or wave) consisting each of two conductors joined together as a loop, the commutator needed would have, therefore,  $K$  segments  $= \frac{1}{2} Z$ . It is easy to see that, using the same commutator, one might double the number of conductors (and double the elec-

tromotive-force of the machine) by substituting for each "element" one consisting of four conductors wound as a double loop. Generalizing, we may say that if each "element" consists of a group of  $g$  conductors, if the number of such groups or elements be called  $G$ , then  $Z = gG = gK$ . In the case of ring-windings, where the simplest element is 1 turn,  $g$  may be any whole number, odd or even. For lap and wave-windings  $g$  must be an even number.

It is possible to go further, and imagine a mixed wave and lap-winding. For, beginning with a wave-winding, each element of which is a mere open loop of 2 conductors such as shown in Fig. 27, one can easily see that for it one might

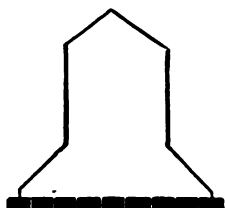


FIG. 27.

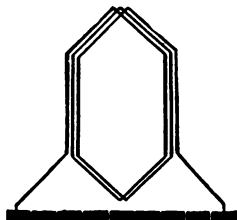


FIG. 28.

substitute a group of, say, six conductors consisting of three laps. Such groups are, indeed, frequently employed in practice, for generating high voltages, as for example in tram-car motors, and in the high-voltage generator of Brown (Fig. 74), since this arrangement lends itself readily to the winding of coils upon formers in the shop.

#### WINDING FORMULÆ.

*Terms used in the Theory.*—It is essential to understand the terms and the sense in which they are used.

Any winding is said to be *re-entrant* which returns on itself so as to form a closed coil. An armature-winding is said to be *singly re-entrant* if it re-enters itself after simply passing in regular order through all the coils arranged around the armature core. Thus an ordinary Gramme ring, or a simple lap-wound drum-armature (Fig. 25), is singly re-en-

trant. There may, if used in a multipolar field, with several sets of brushes at its commutator, be various paths through it; but so far as re-entrancy is concerned it is singly re-entrant. The symbol for a singly re-entrant winding is  $\bigcirc$ .

An armature may be wound with two independent circuits each of which is singly re-entrant. Fig. 29 shows a ring-armature wound thus. These two windings *might* have been furnished with two independent commutators, one at each end. But instead, the number of commutator segments is doubled, the two sets of bars being alternated or imbricated between one another. The brushes must be made broad enough to overlap at least  $2\frac{1}{2}$  bars of the commutator, so as to collect from both windings simultaneously. In a two-pole field, with two sets of broad brushes, this armature would give four paths in parallel from brush to brush. Such a winding is described as *duplex*. The odd numbers form one winding, the even numbers another. Three independent windings with three sets of commutator bars similarly imbricated would be called a *triplex* winding.

An armature is said to be *doubly re-entrant* if its winding only re-enters on itself after having made two passages around the coils of the armature. This term is best elucidated by the example of Fig. 30. This consists of a ring-winding in 17 groups. They are joined together in a way precisely akin to the duplex winding just described; each coil being joined to the next but one, but not to the one immediately next to it. But as the total number of sections is uneven, the coils do not form two separate windings. If we begin with the coil numbered 1, we see it is joined to 3, 5, 7, 9, etc. until we come to number 17, by which time it has completed one round of the periphery, but is not yet re-entrant, for now it goes on to the coils 2, 4, 6, etc., to coil 16, from which it finally re-enters the starting point. The symbol for such a *doubly re-entrant* winding is  $\odot$ . This winding will also require broad brushes that bridge over more than two sections of the commutator at one time. Like the duplex winding of Fig. 29, it doubles the number of paths from brush to brush. In fact, it is electrically the equivalent of a duplex winding save for

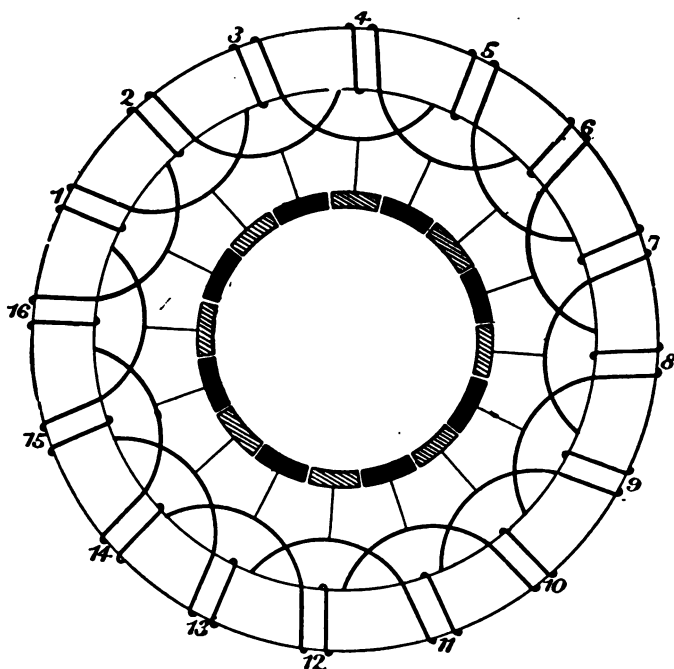


FIG. 29.—DUPLEX WINDING, CONSISTING OF TWO SINGLY RE-ENTRANT RING WINDINGS.

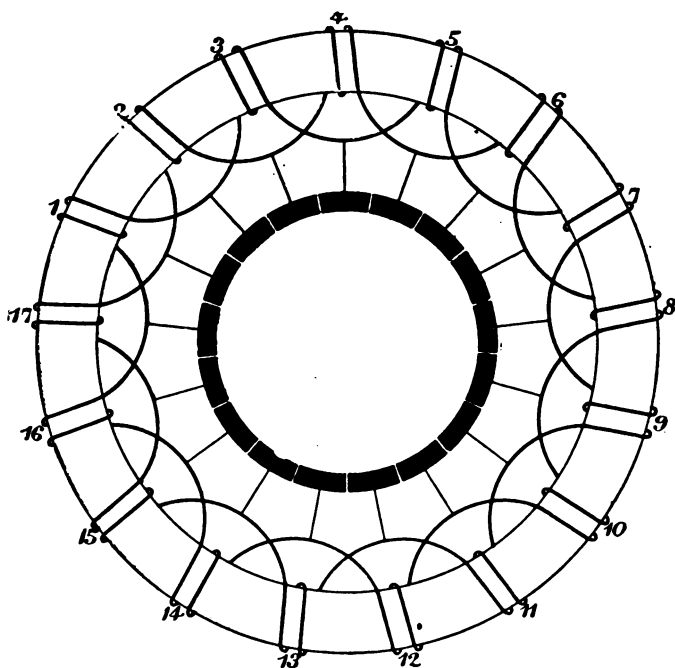




FIG. 30.—DOUBLY RE-ENTRANT RING WINDING.

the fact that it requires an odd number of coils. In armatures of many turns this difference is quite immaterial. For example, an armature with 200 coils as a duplex winding, and a doubly re-entrant armature with 201 coils, if revolved at the same speed in the same field would only differ by  $\frac{1}{2}$  of 1 per cent. in their electromotive-force. Lap-windings may also be made doubly re-entrant, see Fig. 32, p. 95. A *trebly-re-entrant* winding might be made by choosing the number of sections so as to become re-entrant only after a travel completing three rounds of the periphery. For example, a 20-coil ring-winding joined according to the following scheme:—

1—4—7—10—13—16—19—2—5—8—11—14—17—20—3  
—6—9—12—15—18—1. The symbol for treble re-entrancy is . It is the electrical equivalent of a triplex-winding made of three simplex singly re-entrant windings ; and like the triplex-winding will require brushes broad enough to cover  $3\frac{1}{2}$  adjacent commutator bars at least.

Armature windings are also described in terms of the *number of paths* which they afford for the current to follow from the negative brushes through the windings to the positive brushes. This number, in closed coil armatures (which are the only ones here dealt with) is always even. In simplex parallel-wound armatures (whether ring or drum) the number of such paths or circuits is always equal to the number of poles: in duplex parallel-wound armatures to twice the number, and so forth. In simplex series-wound armatures, the number of such paths is always two: in duplex series-wound armatures, four, irrespective of the number of poles. It is common to refer to windings by the number of circuits they present: thus, one speaks of a *ten-circuit* winding, meaning one in which there are ten paths through the winding from — to +. The current in one circuit will be equal to the whole armature current divided by the number of circuits. There are also methods of winding due to Arnold, which result in a *series-parallel arrangement*. Thus it is possible to have a 6-pole machine, with 4 paths through the armature. This might be carried out as a doubly re-entrant wave-winding. (See page 96.)

The next term which requires definition is the *pitch* or *spacing* of the winding. This term denotes the distance from one element of the winding to the next similar element in the succession; and it is usual to express the *pitch* of the winding in terms of the number of conductors spanned over, or less usually in terms of the number of elements of winding (loops, or groups of conductors) passed over, or sometimes in terms of the number of slots passed over. It is not usual to express the pitch, either in actual peripheral length, or in terms of angle subtended, or in terms of the pole-pitch. Suppose all the conductors to be numbered consecutively around the periphery of an armature, and that No. 1 is joined at the front end to No. 16, thus forming a loop, and that No. 16 is joined at the back end to No. 31, then the pitch at both ends is 15. In wave-winding the pitch at both ends is positive, that is to say the winding goes continually forward. In lap-winding the pitch at the two ends is different. Thus, if at the front end No. 1 is joined to No. 18, and if at the back of No. 18 the end connexion laps back to No. 3, the front pitch is + 17, while the back pitch is — 15. In that case the resultant pitch is 2, and the average pitch is 8. We shall use the symbols  $y_1$  and  $y_2$  for the front and back pitches respectively,  $y$  for the total pitch and  $\bar{y}$  for the average pitch. Since it is obvious that the simplest element, whether of lap or wave-winding, is a loop of two conductors united together, and since in every such loop one of the two conductors ought to be passing a south pole at the time when the other is passing a north pole, it follows that the width across the loop ought to be approximately equal to the pole-pitch. In fact the average winding-pitch must be in lap-windings a little less, and in wave-windings a little less or a little greater, than the pole-pitch. In lap-windings the larger of the two pitches may equal the pole-pitch, ought not to exceed it, but may (and with some advantage) be less; while the smaller of the two pitches should not be less than the width of the pole-face.

*Condition of Re-entrancy.*—The condition that a winding shall return after a finite number of symmetrically spaced steps to the conductor from which it starts may be stated thus:—

The resultant step from element to element, multiplied by the number of conductors per element, and by the number of such resultant steps, must equal the whole number of conductors multiplied by some whole number. For example, let a lap-winding consist of 80 simple loops, having a resultant pitch  $= \cancel{8}$ . This will be re-entrant if the whole number of such conductors is 160. In the case of wave-windings, where the loops go zig-zagging around the periphery, the number of elements per round, multiplied by the number of rounds, and by the number of conductors per element, will obviously give the whole number of conductors so united. Now the pitch must be such as to be approximately equal to the pole-pitch, but not exactly, otherwise the winding would become re-entrant at the first round. Or conversely, the whole number of conductors must be such that with a winding-pitch approximately equal to the pole-pitch, the winding shall become re-entrant only after a number of rounds. Thus, for example, in an 8-pole machine, with single winding pitch 25, the total number of conductors must *not* be  $25 \times 8 = 200$ , otherwise the winding would re-enter after the first round of 4 loops. It might be either 198 or 202, for then round after round would be completed before re-entrancy was finally attained. This example illustrates so well the essential principle of a simplex wave-winding that it may be further considered. Suppose we construct a winding table for this winding, using  $202 = Z$ . Take the even numbers of the conductors as going down from front to back; the ~~even~~<sup>odd</sup> numbers being the return conductors leading up from back to front. Starting with No. 1 the connexions run as follows:—

1—26—51—76—101—126—151—176—201, the eighth step thus completing the first round, and failing to re-enter by 2 places. The second round of eight steps similarly goes from 201 to 199, the third to 197, and so forth. The winding thus recedes 2 places at each round. By the end of the twenty-fifth round 200 steps will have been taken, and the winding will have slipped back 50 conductors from No. 1, and the 200th step will therefore end on No. 153. There remain two steps to be taken, viz. from 153 to 178, and from 178 to No. 1, thus

WINDING TABLE FOR 8-POLE DRUM ARMATURE; 202 CONDUCTORS;  
SERIES GROUPING; BRUSHES ( $\pm$ )  $135^\circ$  APART.

F	B	F	B	F	B	F	B	F
D	U	D	U	D	U	D	U	
1	26	51	76	101	126	151	176	
201	24	49	74	99	124	149	174	
199	22	47	72	97	122	147	172	
197	20	45	70	95	120	145	170	
195	18	43	68	93	118	143	168	
193	16	41	66	91	116	141	166	
191	14	39	64	89	114	139	164	
189	12	37	62	87	112	137	162	
187	10	35	60	85	110	135	160	
185	8	33	58	83	108	133	158	
183	6	31	56	81	106	131	156	
181	4	29	54	79	104	129	154	
179	2	27	52	77	102	127	152	
177	202	25	50	75	100	125	150	
175	200	23	48	73	98	123	148	
173	198	21	46	71	96	121	146	
171	196	19	44	69	94	119	144	
169	194	17	42	67	92	117	142	
167	192	15	40	65	90	115	140	
165	190	13	38	63	88	113	138	
163	188	11	36	61	86	111	136	
161	186	9	34	59	84	109	134	
159	184	7	32	57	82	107	132	
157	182	5	30	55	80	105	130	
155	180	3	28	53	78	103	128	
153	178	1						

finally completing the re-entrancy. Fig. 31 illustrates the first two rounds of this winding. It is assumed, but not shown that the winding is in two layers; the conductors in the upper layer being those with odd numbers, those in the under layer with the even numbering. On examining this table it will

be seen that the conductor which is half way through the winding from No. 1, is No. 102. These are not at opposite ends of a diameter, but are  $\frac{1}{8}$  of a circumference apart. As a matter of fact the brushes—two sets of which only are essential, as there are only two circuits through the winding—may be either  $\frac{1}{8}$ ,  $\frac{3}{8}$  or  $\frac{5}{8}$  of a circumference apart. In one sense this winding has a 25-fold re-entrancy, seeing that at every 8 steps

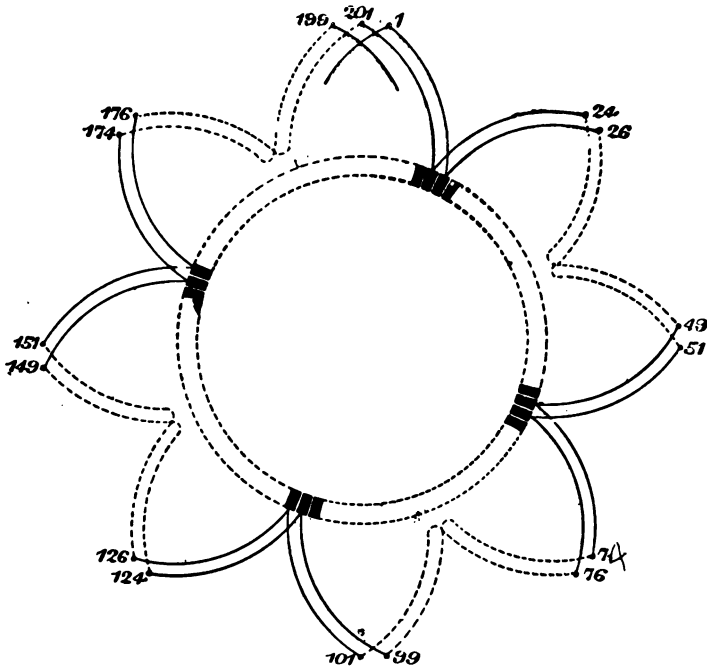


FIG. 31.—WAVE-WINDING: 8-pole, 2-circuit, singly re-entrant.

the periphery is perambulated. But, strictly, the winding is only singly re-entrant. Had there been 204 conductors, or 196 conductors, so that at each round of eight steps the winding receded or advanced by four places (instead of 2 places), the result would have been different, giving a doubly re-entrant winding with four paths. The number of paths through the armature corresponds to the number 2, 4, or 6, etc., by which the first round fails of re-entrancy. In the case illustrated

by the winding table we see that the principle of re-entrancy enunciated at the beginning of this paragraph is fulfilled, for the resultant step of 30 multiplied by the number which is 2, of conductors per element, multiplied by the number of resultant steps, namely  $(25 \times 4) + 1$ , makes 6060, which is an integral multiple of the whole number of conductors 202.

*Condition of each Conductor being encountered once.*—It is not enough that the winding should be re-entrant. It should (in a simply re-entrant winding) be such that *all* the conductors should be encountered, and that each should be encountered once only.

*Case I. Lap-Windings.*—Let  $y_1$  be the forward pitch and  $y_2$  the backward pitch, its actual value being negative. Then  $y_1 + y_2$  is the resultant step. If we confine ourselves to the practical case that each element or section of the winding is a simple loop, the number  $s$  of such sections will be equal to  $\frac{Z}{2}$ ;

and the number of sections (which is the same as the number of resultant steps if multiplied by the length of each resultant step) will equal the total travel of the winding. This will be equal to  $Z$  if the winding is singly re-entrant. But if the lap has been such (for example if  $y_1$  is 25 and  $y_2$  is  $-21$ , then  $y_1 + y_2 = 4$ ) that re-entrancy is not effected without travelling more than once round the periphery, then the total travel will be equal to  $U Z$ , where  $U$  is the number of times the periphery has been travelled round. This gives us as the first condition that

$$\frac{Z}{2} (y_1 + y_2) = U Z;$$

whence

$$\frac{y_1 + y_2}{2} = U. \quad (1)$$

Now  $U$  may be 1, 2, or any whole number; hence it follows that  $y_1 + y_2$  must in *every* case be an *even* number. Further, the condition that no conductor shall be encountered twice is that for no number of steps whatever shall  $y_1 + y_2$ , however

often repeated, be equal to  $y_1$ . Or taking  $m$  as any whole number

$$m(y_1 + y_2) \geq y_1;$$

whence

$$\frac{y_1}{y_2} \geq \frac{m}{1-m} \quad . \quad . \quad (2)$$

It follows from this inequality that  $y_1$  and  $y_2$  *cannot possibly have any common factor*, and as their difference must be even, it follows that *both of them must be odd numbers*.

*Case II. Wave-Windings.*—The resultant step for an element being  $y_1 + y_2$ , and the number of such steps being  $\frac{Z}{2}$  and the total travel being  $U$  times round the periphery, we have

$$\frac{Z}{2}(y_1 + y_2) = UZ;$$

whence also

$$\frac{y_1 + y_2}{2} = U. \quad . \quad . \quad (3)$$

In the case of the winding-table given above where  $y_1$  and  $y_2$  are each 25, the total travel is 25 times round the periphery. Now in order that no conductor be encountered twice it is clear that not by any number of repetitions of the step  $y_1 + y_2$  shall it be possible to recur to the step  $y_1$  beyond any previous number of the repetitions of the step  $y_1 + y_2$ . Or, if  $m$  and  $n$  are any whole numbers it is clear that  $m$  times  $y_1 + y_2$  must *not* equal  $n$  times  $y_1 + y_2$  steps plus  $y_1$ . Or in symbols

$$m(y_1 + y_2) \geq n(y_1 + y_2) + y_1. \quad . \quad (4)$$

It follows that in this case also  $y_1$  and  $y_2$  *cannot have any common factor*; and as  $U$  may be any number, odd or even, it follows from [3] that as their sum must be even, both of them may be odd. They may be, however, equal to one another, and this is the common case.

*General Formulae.*—We are now ready to state the general

formulae for windings. These may be put either (1) in terms of the number of segments  $K$  of the commutator, and of the pitch of the winding  $y_k$  in terms of the number of commutator segments over which the element of the winding spans, or (2) in terms of the number of conductors  $Z$  and of the pitches  $y_1$  and  $y_2$  as defined above.

These general formulae are as follows:—

If  $y$  stands for the complete step, not from conductor to conductor, but from the first conductor of any group to the first conductor of the next group,  $m$  for the field step, and  $G$  for the total number of groups in the winding, we shall have

$$\frac{1}{2}py \pm c = mgG = mZ \quad . \quad . \quad (1)$$

when

$$Z = \frac{py \pm 2c}{2m}; \quad . \quad . \quad . \quad (2)$$

and

$$y = \frac{2mZ \mp 2c}{p} \quad . \quad . \quad . \quad (3)$$

which are the general formulae for symmetrical windings.

For *lap-windings*  $m = 0$ , where it follows that

$$y = \mp \frac{2c}{p}; \quad . \quad . \quad . \quad (4)$$

$y$  being dissected into 2 parts  $y_1$  and  $y_2$ , of which  $y_2$  is negative, each of which is either equal to or slightly less than  $Z/p$ , and which differ from one another by  $2c \div p$ .

For *wave-windings*  $m = 1$ , so that the complete step becomes

$$y = \frac{2Z \mp 2c}{p}; \quad . \quad . \quad . \quad (5)$$

and if this is made up of two equal back and front pitches  $y$  and  $y_2$  of equal value, we shall have

$$y_1 = y_2 = \frac{Z \mp c}{p} \quad . \quad . \quad . \quad (6)$$

In lap-windings the step of the winding at the commutator is related to winding pitch by the simple rule:—

$$y_k = y \div g \quad . \quad . \quad . \quad (7)$$

Thus in a simple lap-winding, where  $y = 2$ , and where each

element of the winding is a simple loop made of two conductors so that  $g = 2$ , we have  $y_k = 1$ .

It would be easy to write out a number of special formulæ for special cases. Four each of lap and wave must suffice.

#### LAP-WINDINGS.

(i.) *Simplex Singly Re-entrant (Parallel) Lap-Winding.*

$c = p$ ;  $m = 0$ ; and, if  $g = 2$ ;  $Z = 2G = 2K$ .

$$y = \pm 2;$$

$$y_1 \leq \frac{Z}{p} \quad \text{and must be odd;}$$

$$-y_2 = y_1 + 2;$$

$$y_k = 1.$$

(ii.) *Duplex or Multiplex (Parallel) Lap-Winding*, consisting of  $x$  independent windings, each of which is a simplex singly re-entrant lap-winding.

$c = px$ ;  $m = 0$ ; and if  $g = 2$ ,  $Z = 2G = 2K$ .

$$y = \pm 2x;$$

$$y_1 \leq \frac{Z}{p} \quad \text{and must be odd;}$$

$$y_2 = y_1 - 2x;$$

$$y_k = \pm x.$$

(iii.) *Simplex (Series Parallel) Doubly or Multiply Re-entrant Lap-Winding.* (See remark on p. 83 as to meaning of term.)  $c = 4, 6$ , or other even number greater than 2;  $m = 0$ ; and if

$g = 2$ ,  $Z = 2G = 2K$ .

$$y = \pm c;$$

$$y_1 \leq \frac{Z}{p} \quad \text{and must be odd;}$$

$$y_2 = y_1 - c;$$

$$y_k = \pm \frac{1}{2} c.$$

(iv.) *Duplex or Multiplex (Series-Parallel) Doubly or Multiply Re-entrant Lap-Winding*, consisting of  $x$  independent windings, each of which is a simplex doubly or multiply re-entrant lap-winding. Here  $x = 2, 3, 4$  or any whole number;  $c_1$  = the number of circuits through any one of the independent series parallel windings (may be 4, 6, or other even number higher than 2);  $m = 0$ ; and if  $g = 2, Z = 2 G = 2 K$ .

$$y = \pm x c_1;$$

$$y_1 \leq \frac{Z}{p} \quad \text{and must be odd;}$$

$$y_2 = y_1 - x c_1;$$

$$y_k = \pm \frac{1}{2} x c_1.$$

Figs. 32 and 33 afford examples of case ii. and case iii. above. Fig. 32 is a duplex lap-winding in which  $p = 4, Z = 32, y_1 = +9$  and  $y_2 = -5$ . There are two independent circuits exactly as in the duplex ring-winding, Fig. 29, p. 84. Symbol  $\circ \circ$ . Fig. 33 corresponds to the doubly re-entrant ring-winding, Fig. 30, p. 84. In it  $p = 4, Z = 34, y_1 = +9$  and  $y_2 = -5$ . Symbol  $\odot$ . In both cases  $c = 8$ .

#### WAVE-WINDINGS.

(i.) *Simplex Singly Re-entrant (Series) Wave-Winding*.

$c = 2$ ;  $m = 1$ ; and if  $g = 2, Z = 2 G = 2 K$ .

$\bar{y}$  is the average of  $y_1$  and  $y_2$ .

$$Z = p \bar{y} \pm 2;$$

$$y_1 = y_2 = \frac{Z \mp 2}{p} \quad \text{and must be odd, and must not have any common factor with } Z.$$

$$y_k = \frac{2 K \mp 2}{p}.$$

(ii.) *Duplex or Multiplex (Series) Wave-Winding*, consisting of  $x$  independent singly re-entrant simplex wave wind-

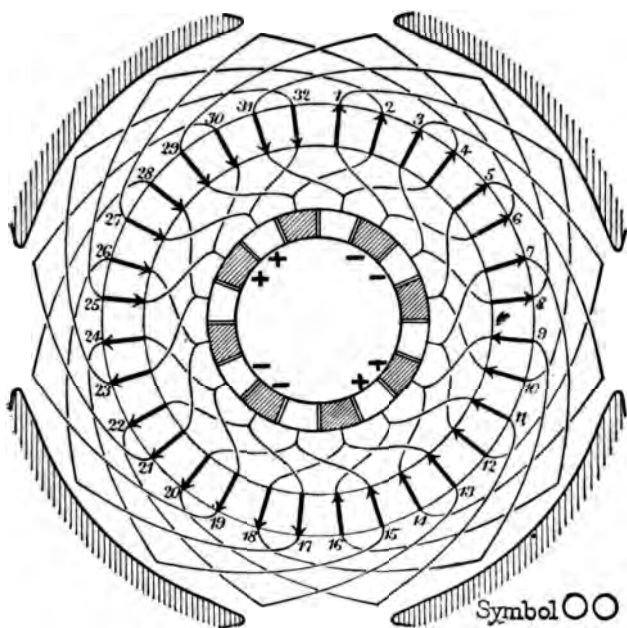


FIG. 32.—DUPLEX LAP-WINDING.

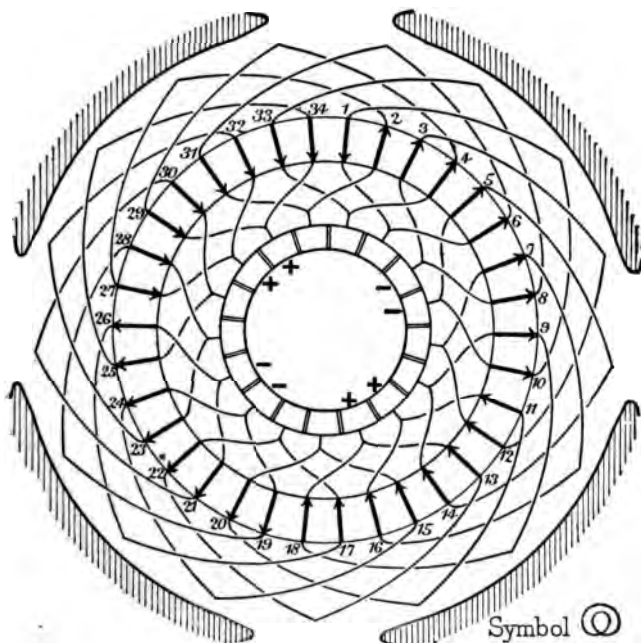


FIG. 33.—SIMPLEX DOUBLY RE-ENTRANT LAP-WINDING.

ings.  $x = 2, 3, 4$ , or any whole number; the number of circuits  $c_1$ , in any one of the simplex windings  $= 2$ ;  $m = 1$ ; and if  $g = 2$  then  $Z = 2 G = 2 K$ . Number of circuits in parallel  $= c_1 x$ .

$$Z = x p \bar{y} \pm 2x;$$

$$y_1 = y_2 = \frac{Z \mp 2x}{xp}; \quad \text{In those cases where } \bar{y} \text{ is even, } y_1 \text{ may } = \bar{y} + 1, \text{ and } y_2 = \bar{y} - 1.$$

$$y_k = \frac{2 K \mp 2x}{xp}.$$

(iii.) *Simplex Doubly or Multiply Re-entrant* (series-parallel) *Wave-Winding*; also called *Arnold's winding*.  $c = 4, 6$ , or other even number higher than 2;  $m = 1$ ; and, if  $g = 2$ ,  $Z = 2 G = 2 K$ .

$$Z = p \bar{y} \pm c;$$

$$y_1 = y_2 = \frac{Z \mp c}{p};$$

$$y_k = \frac{2 K \mp c}{p}.$$

(iv.) *Duplex or Multiplex Doubly or Multiply Re-entrant* (Series-Parallel) *Wave-Winding*, consisting of  $x$  independent wave-windings each of which is doubly or multiply re-entrant.  $c_1 = 2, 4, 6$ , or other even number; number of circuits in parallel  $= c_1 x$ ;  $m = 1$ ; if  $g = 2$ , then  $Z = 2 G = 2 K$ .

$$Z = x p \bar{y} \pm c_1 x;$$

$$y_1 = y_2 = \frac{Z \mp c_1 x}{xp};$$

$$y_k = \frac{2 K \mp c_1 x}{xp}.$$

The circumstance that if in a wave-winding  $\bar{y}$  and  $Z$  have any common factor there will be a corresponding number of independent windings, leads to some curious results. Further the circumstance that if in any wave-winding the number of circuits is made equal to the number of poles, leads to the result that in this case the wave-winding becomes identical to

a simple lap-winding or ring-winding. In the case of bipolar machines wave and lap-windings are identical, the only difference being the question whether  $y_1 = y_2$  or not. A series grouping cannot be effected by a lap-winding: it may be effected by a wave-winding or by a mixture of wave and lap-winding. In the case of 4-pole, 8-pole and 12-pole machines, a simplex series winding cannot be made with 4 conductors per segment of the commutator. Nor, in the case of 6-pole and 12-pole machines can a simplex series winding be made with 6 conductors per segment. In general, for a machine with  $n$ -poles or  $2n$  or  $3n$ -poles, it is impossible to make a two-circuit winding having  $n$  conductors per segment of the commutator. Or, stated another way, to make a two-circuit wave-winding, the number of conductors must not be a multiple of the number of poles.

The number of circuits made by any winding can be calculated by the following formulæ, derived from those previously given.

*Lap-Windings.*

$$c = \frac{1}{2} p y. \quad . \quad . \quad . \quad (a)$$

*Wave-Windings.*

$$c = Z - p y_1 \quad . \quad . \quad . \quad (\beta)$$

if  $y_1 = y_2$ . If not, then take instead of  $y_1$  the *average* pitch.

*Ring-Windings (parallel.)*

$$c = p y. \quad . \quad . \quad . \quad (\gamma)$$

*Examples:—*(i.)  $p = 6$ ;  $Z = 374$ ;  $K = 187$ ;  $y_1 = 47$ ,  $y_2 = -45$ ;  $c = 6$ . Here  $y = 2$ , the winding being a simple lap-winding.

(ii.)  $p = 6$ ;  $Z = 434$ ;  $y_1 = 73$ ,  $y_2 = 71$ . This is a wave-winding with average pitch of 72. Hence by formula ( $\beta$ ), there will be two circuits only, the winding being singly re-entrant. Symbol O.

(iii.)  $p = 6$ ;  $Z = 442$ ;  $y_1 = 71$ ;  $y_2 = -67$ . This is a lap-winding, with  $y = y_1 + y_2 = 71 - 67 = 4$ . Hence by formula ( $a$ ) there will be 12 circuits, the winding being duplex singly re-entrant. Symbol O O.

(iv.)  $p = 8$ ;  $Z = 572$ ;  $y_1 = 71$ ,  $y_2 = 71$ . This is a wave-winding, giving by formula ( $\beta$ ) 4 circuits, the winding being doubly re-entrant. Symbol @.

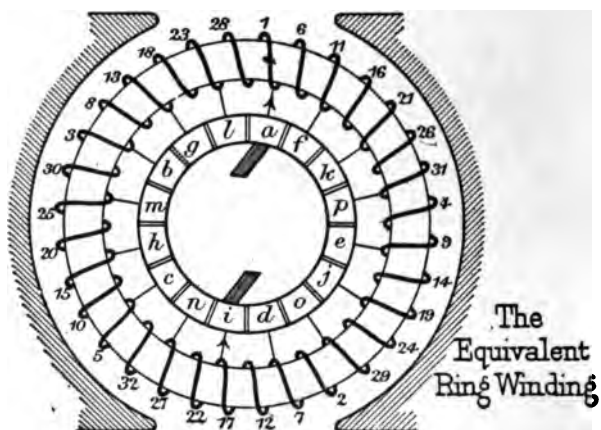
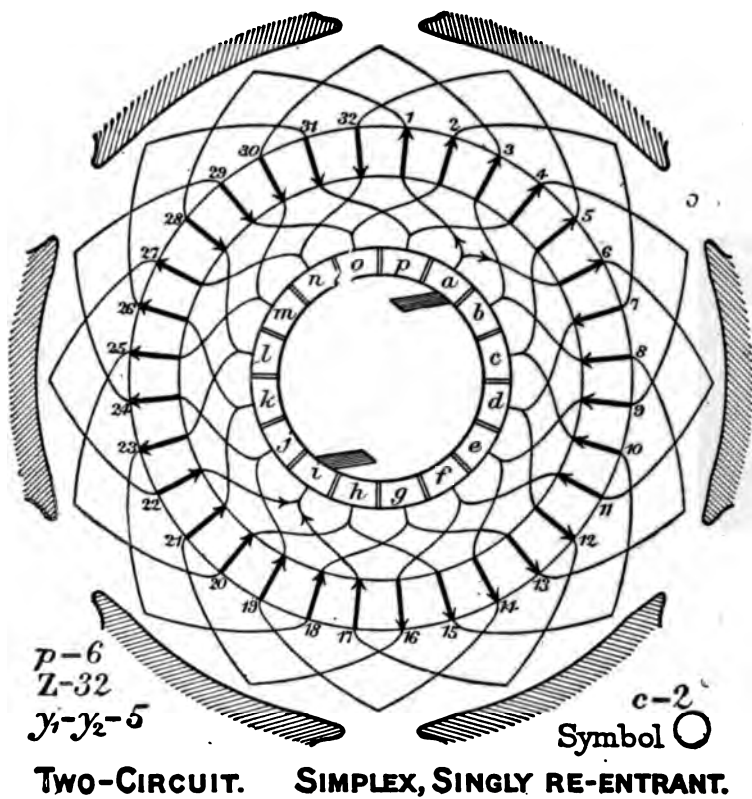
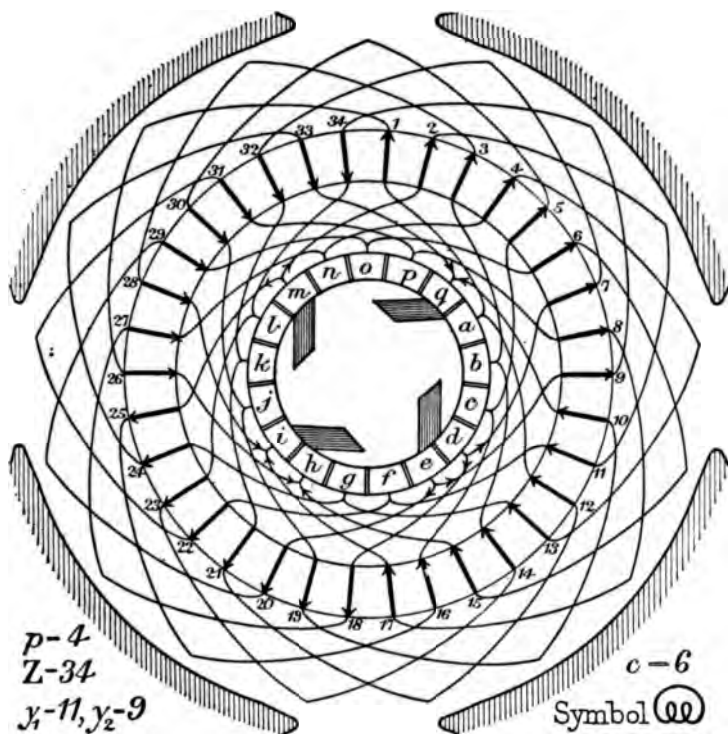


FIG. 34.



SIX-CIRCUIT. SIMPLEX, TREBLE RE-ENTRANT.

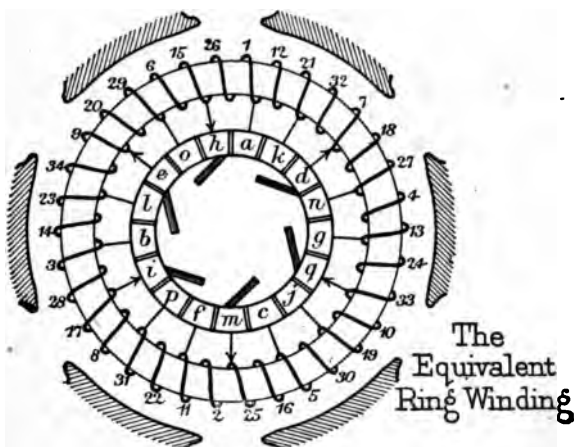


FIG. 35.

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(v.)  $p = 4$ ;  $Z = 246$ ;  $y_1 = 61$ ,  $y_2 = 59$ . This is a wave-winding with average pitch 60, giving 6 circuits, with a trebly re-entrant winding. Symbol  $\textcircled{60}$ .

(vi.)  $p = 4$ ;  $Z = 438$ ;  $y_1 = y_2 = 111$ . This is a wave-winding, but as  $Z$  and  $y_1$  contain 3 as a common factor there will be 3 independent wave-windings, each singly re-entrant; and there will be 6 circuits. Symbol  $\textcircled{0} \textcircled{0} \textcircled{0}$ .

Figs. 34 to 39 give a set of examples of wave-windings to elucidate the rules.

Fig. 34 is a 6-pole, two-circuit winding (sometimes called "multipolar series"), with 32 conductors. The winding is singly re-entrant. The winding pitch  $y_1 = y_2 = 5$ . Hence by the rule  $c = Z - p y$ , there will be two circuits. Below the figure is shown the equivalent ring, having the 32 conductors rearranged in the order of their occurrence (see Arnold's "reduced scheme," p. 112), the two circuits implying a two-pole field. The advantage of this mode of representation is that in the equivalent ring the windings do not overlap one another.

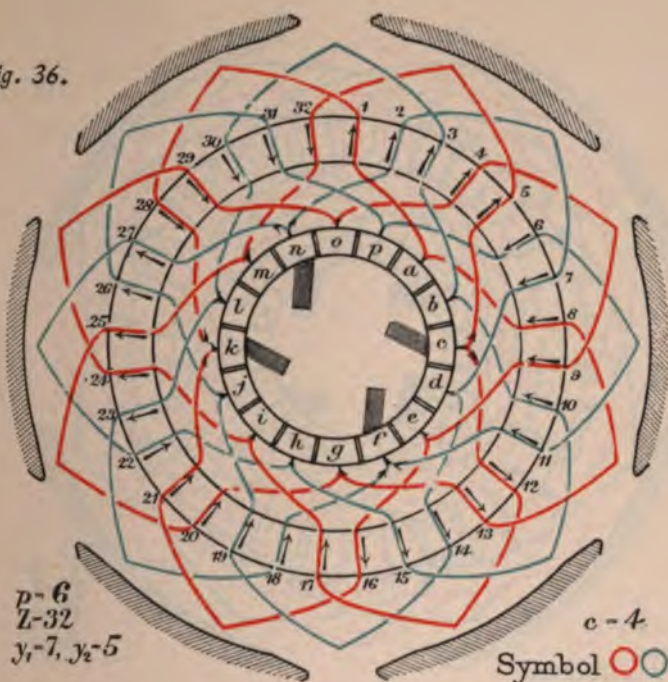
Fig. 35 depicts a 4-pole, six-circuit winding, with 34 conductors and an average winding-pitch of 10. On examination it will be seen that the winding, though simplex, is trebly re-entrant (symbol  $\textcircled{30}$ ), making 6 circuits though there are only 4 brushes, in correspondence with the 4 poles. The equivalent ring, as shown, will be a 6-pole ring with 6 brushes.

Fig. 36 is a 6-pole, four-circuit winding, having 32 conductors with an average winding pitch of 6. This produces a duplex-winding; there being two independent windings each singly re-entrant. Hence there are four circuits (symbol  $\textcircled{0} \textcircled{0}$ ). The equivalent ring will, of course, have a 4-pole field and 4 brushes.

Fig. 37 is a 4-pole, eight-circuit winding, having 32 conductors, with an average winding pitch of 10. It results in a duplex, doubly re-entrant winding (symbol  $\textcircled{20} \textcircled{20}$ ). The equivalent ring has 8 poles and 8 brushes.

Fig. 38 is a 4-pole, six-circuit winding, with 30 conductors and a winding pitch of 9. As there is the common factor 3 between  $\frac{1}{2} Z$  and  $y$ , there will be three independent windings,

Fig. 36.



FOUR-CIRCUIT. DUPLEX, SINGLY RE-ENTRANT

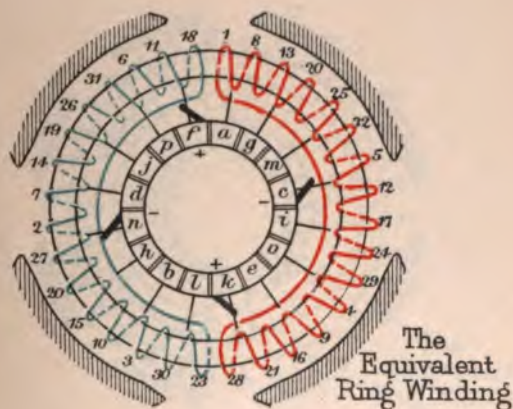
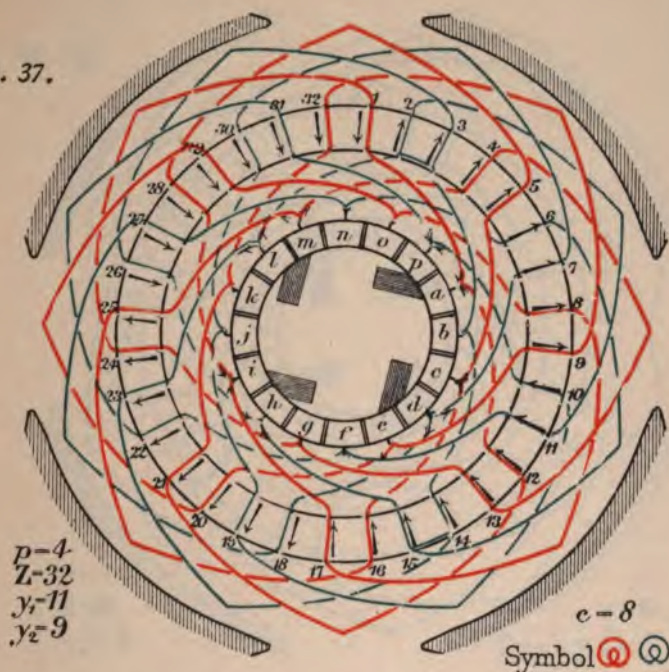
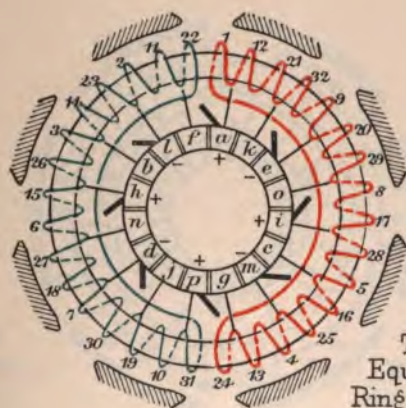




Fig. 37.



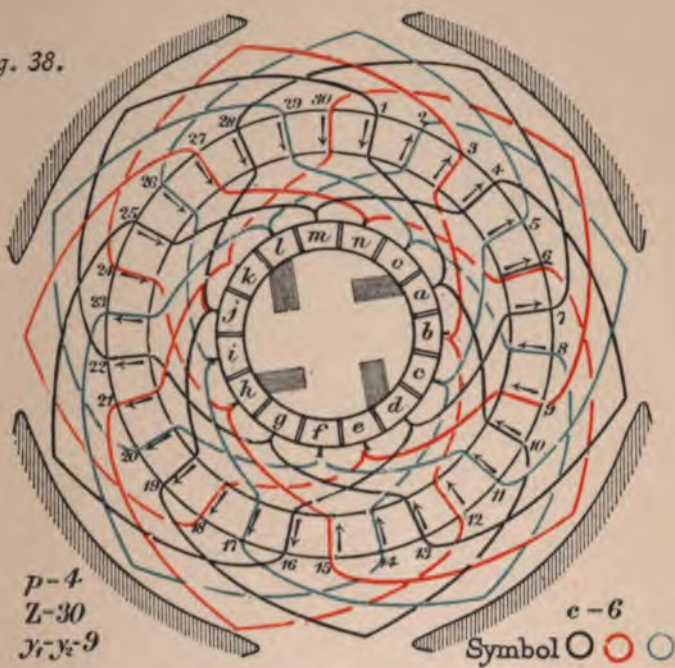
EIGHT-CIRCUIT. DUPLEX, DOUBLY RE-ENTRANT.



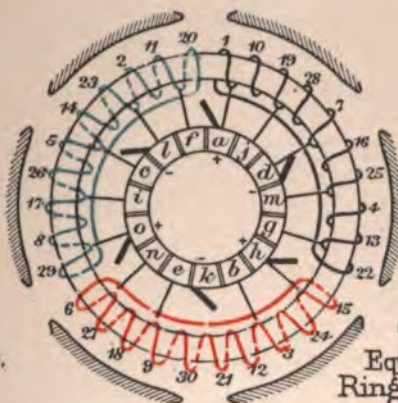
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 Spon & Chamberlain,  
 New York, N. Y.



Fig. 38.



# SIX-CIRCUIT. TRIPLEX, SINGLY RE-ENTRANT



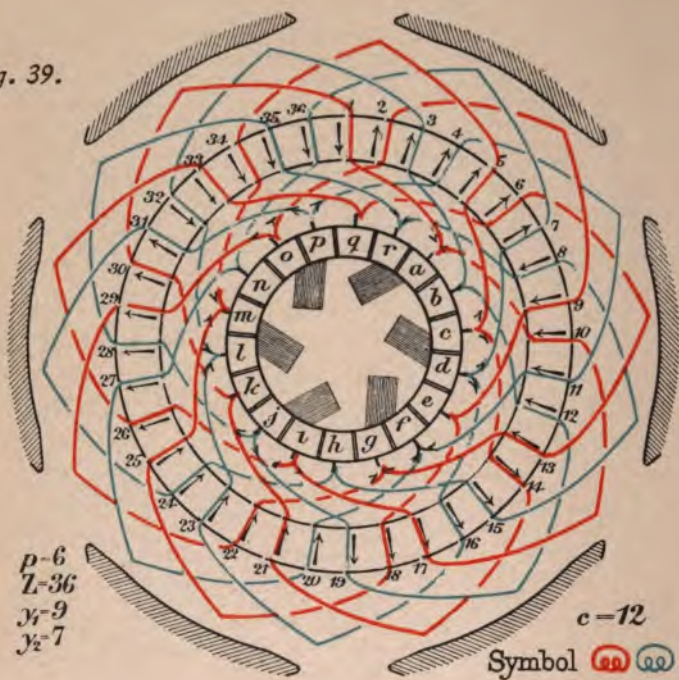
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 New York, N. Y.

The  
 Equivalent  
 Ring Winding

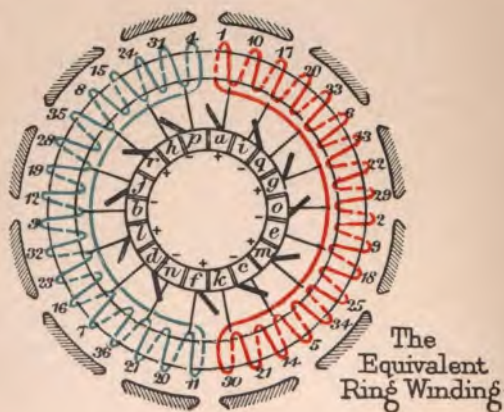




Fig. 39.



TWELVE-CIRCUIT. DUPLEX, TREBLE RE-ENTRANT



coloured respectively red, green and black, and each is singly re-entrant, so that there are 6 circuits (symbol  $\bigcirc \bigcirc \bigcirc$ ). This triplex winding should be compared with Fig. 35, which also results in a six-circuit winding. The equivalent ring has, of course, also three independent windings.

Fig. 39 is a 6-pole, twelve-circuit winding, with 36 conductors, and an average winding pitch of 8, resulting in a duplex trebly re-entrant winding (symbol  $\bigcirc \bigcirc \bigcirc \bigcirc \bigcirc \bigcirc$ ). It requires but 6 broad brushes, though, as is obvious from the equivalent ring diagram, it has 12 circuits in parallel one with another.

It will be noted that Figs. 34 and 36 depict two cases in each of which there are 6 poles and 32 conductors. They differ,

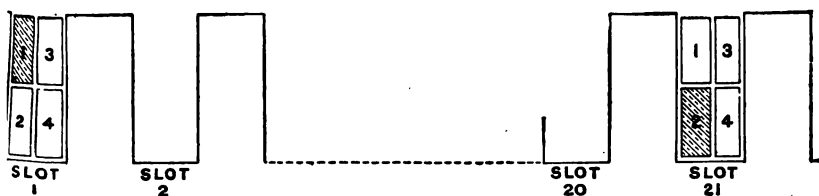


FIG. 40.

however, in the winding-pitch, with the result that one is a two-circuit and the other a four-circuit winding. The latter would yield double the current at half the voltage.

*Further Examples of Drum-Windings.*—An example of a lap-winding is afforded by the 6-pole Scott and Mountain generator, page 160, in which  $Z = 496$ ,  $K = 248$ ,  $g = 2$ ,  $c = 6$ ,  $y_1 = 41$ ,  $y_2 = -39$ ,  $y = 2$ , the conductors lying in 124 slots, 4 conductors per slot. As there are 6 poles there are  $20\frac{2}{3}$  slots per pole. The coils are grouped to span over 20 slots, conductor No. 1 (upper) in No. 1 slot being united to conductor No. 2 (lower) in No. 21 slot; and No. 2 in No. 21 slot is connected back to No. 3 (upper) in No. 1 slot, which in turn is joined to No. 4 (lower) in No. 21 slot, as shown in Fig. 40. This is then returned to No. 1 (upper) in No. 2 slot, and so forth. If the conductors were numbered consecutively, beginning with No. 1, in No. 1 slot, those in No. 21 slot would

become Nos. 41, 42, 43 and 44. Hence if No. 1 is joined at the front end to No. 42, and No. 42 at its back end laps back to No. 3, the pitches are respectively  $y_1 = 41$ ,  $y_2 = -39$ , and  $y = 2$ . This is therefore a simplex singly re-entrant winding.

As an example of a wave-winding we may take the 10-pole generator of Kolben (page 216 and Plate VI.). This has 874 conductors lying in 437 slots, *i.e.* two conductors per slot. Now  $874 = 87 \times 10 + 4$ . Hence if  $\bar{y} = 87$ , it follows that  $c = 4$ , and the winding will be doubly re-entrant, or is a series-parallel winding. The winding table may be constructed as follows, beginning with conductor No. 1:—

1st round . . .	1	88	175	262	349	436	523	610	697	784	871
2nd round . . .	871	84	171	258	345	432	519	604	693	780	867
3rd round . . .	867	80	167	254	341	428	515	600	689	776	863
. . . . .											
44th round . . .	703	790	3	90	177	264	351	438	525	612	699
45th round . . .	699	786	873	86	173	260	347	434	521	608	695
. . . . .											
87th round . . .	531	618	705	792	5	92	179	266	353	440	527
88th round . . .	527	614	701	788	1						

The winding becomes re-entrant after 87 rounds plus 4 steps. It had become all but re-entrant by returning to No. 3 (instead of No. 1) after 44 rounds plus 2 steps.

*Mixed Wave and Lap-Winding.*—None of the foregoing formulæ take any account of certain symmetrical windings in practical use which are mixed. Fig. 42 is a simple example of such a winding, essentially a wave-winding, of which each element consists of 4 loops in series. Windings of this general character lend themselves to small or medium sized armatures with former-wound coils, as those of tramway motors, or for special high-voltage construction. An example is to be found in the high-voltage 4-pole dynamo of Messrs. Brown, Boveri & Co., page 205. This is a winding of great interest. There are 59 slots, receiving 59 former-wound groups of coils. Each group is made up of three separate "sections," so that the number of "sections" is 177, and there are 177 segments to the

commutator. These sections are connected up as a wave-winding. But each section itself consists of 4 loops or turns. There are therefore 24 wires through each slot, making 1316 conductors in all. They may be regarded as 177 "sections," each consisting of 8 conductors united together; or, for purposes of calculation we may regard the whole thing as a wave-winding of 354 conductors, and then substitute 8 conductors for the 2 in each loop. Now to make a singly re-entrant wave-winding

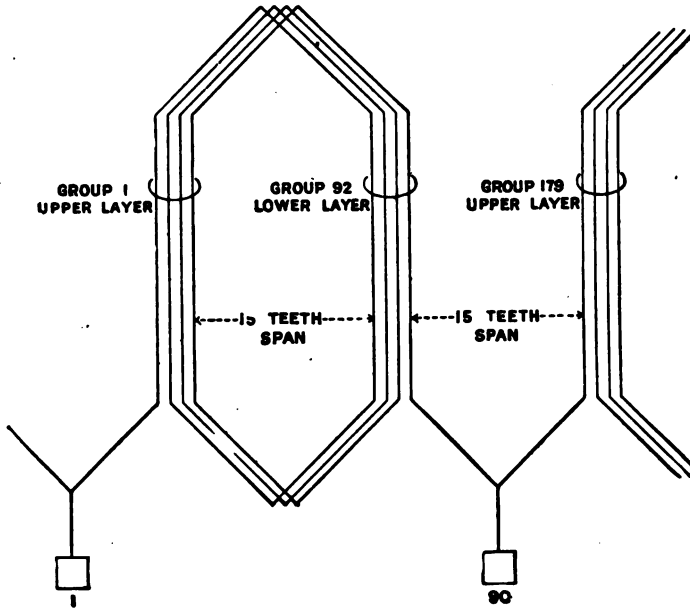
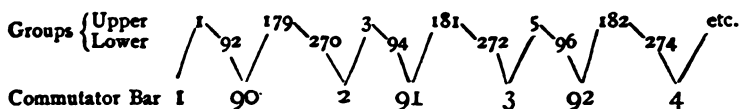


FIG. 41.

of 354 conductors we must have an average pitch  $\bar{y}$  such that  $p\bar{y} \pm 2 = 354$ ; whence  $\bar{y} = 89$  or 88. As a matter of fact the average pitch chosen is 89, and the two actual pitches are  $y_1 = 87$ ,  $y_2 = 91$ , the winding table being as follows:—

First round	1—92—179—270—3
	91 87 91 87
Second round	3—94—181—272—5
	91 87 91 87

and so forth. But the steps of pitch 91 are all of them laps of 4 turns, while the steps of pitch 87 are mere connexions down to the commutator and then on to the next set of 4 turns in the succession, as in the following scheme:—



Now as there are 354 "groups" in 59 slots this is 6 "groups" per slot, three "upper" of odd number and three "lower" of even number. As there are 6 in a slot we may take No. 1 slot as containing groups 1 to 6, No. 2 slot groups 7 to 12, and so forth, so that No. 16 slot will contain 91 to 96. Then group 92 will be the first lower group in No. 16 slots, and the

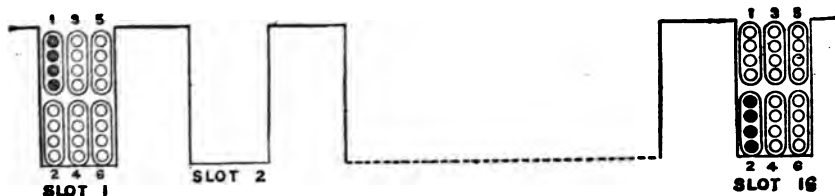


FIG. 42.

slot-pitch for the former-wound coils will be from No. 1 slot to No. 16 slot, or the slot-pitch for the coils spans over 15 teeth.

*Number of Brush-sets.*—The number of places on the commutator at which it is necessary or advisable to place a set of collecting brushes can be ascertained from the winding diagrams. All that is necessary is to draw arrows marking the directions of the induced electromotive-forces. This has been done, for example, in the radial diagrams Figs. 34 to 39. Whenever two arrow-heads meet at any segment of the commutator there a positive brush is to be placed: and at every point from which two arrows start in opposed directions along the winding, there is the place for a negative brush.

For all *lap-windings*, and for ordinary *parallel ring-windings*, there will be as many brush-sets as poles, and they will be situated symmetrically around the commutator in regular alternation,  $+$  and  $-$ , at angular distances apart equal to the pole-pitch. It must be remembered that the number of brush-sets does not necessarily show the number of circuits through the armature. Take the case of a 4-pole machine with four sets of brushes at  $90^\circ$  apart from one another. If the winding is a simplex, singly re-entrant lap-winding, there will be 4 circuits. But if the winding is a duplex, or a doubly re-entrant lap-winding, there will be 8 paths. If a triplex singly re-entrant lap-winding there will be 12 circuits.

For *wave-windings*, whether series or series-parallel, and for series ring-windings, if the arrow-heads are similarly drawn it will be found that there are required but two brush-sets, whatever the number of poles; and the angle between the  $+$  set and the  $-$  set will be the same as the angle between any **N**-pole and any **S**-pole. Thus for a 10-pole machine with wave-wound armature, the brush-sets may be  $36^\circ$  apart, or they may be  $3 \times 36^\circ = 108^\circ$ , or  $5 \times 36^\circ = 180^\circ$  apart. But it must again be remembered that though there *may* be only two brush-sets, the number of circuits through the winding is not necessarily 2. For if the winding is duplex, or if it is doubly re-entrant, the number of circuits will be 4. If both duplex and doubly re-entrant, 8.

There are, however, some further considerations that deserve attention.

*Reduction in number of Brush-sets.*—Cases occur when it may be desirable, with a parallel-winding (for which the number of brush-sets would naturally be equal to the number of poles), to reduce the number of brush-sets. In the case of 4-pole tramway motors mere convenience of access dictates the reduction of the number of brush-sets to 2. Now, if a wave-winding is adopted the number will naturally be 2, not 4. If a parallel winding is adopted the number 4 may be reduced to 2 by the application of Mordey's device of cross-connecting the segments of the commutator. Let us, however, consider what is the result, without resorting to either of these expedients, of

simply using, with a parallel-wound 4-pole armature, 2 brushes instead of 4. Suppose the machines to be generating 120 amperes; then if 4 brushes are used there will be 4 circuits, each carrying 30 amperes, and at each "brush" the current will be 60 amperes (Fig. 43). If now 2 of the brushes are removed, and the dynamo still generates 120 amperes, the current through each of the two remaining brushes will be 120 amperes; while internally there will be only 2 circuits. But these will not take equal shares of the current since, though the sum of the electromotive-force in each circuit is the same, the resist-

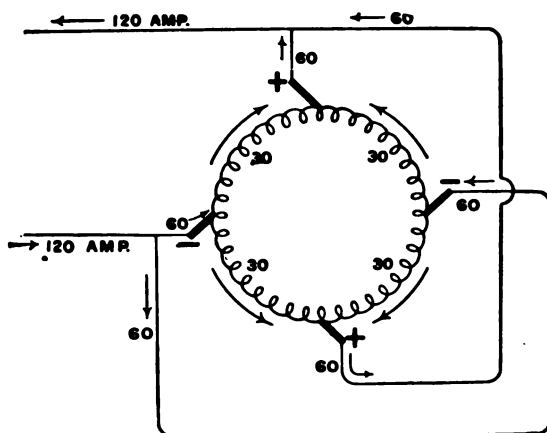


FIG. 43.

ance of one is three times that of the other. So the currents will be about 90 amperes in one circuit, and about 30 amperes in the other as in Fig. 44. Assuming that no spark-difficulties occur in collecting 120 amperes at either brush the arrangement will work perfectly. But the heat losses will be greater than before. For, if the resistance of one-quarter of the winding be taken as 0.05 ohm, the heat loss will be :-

<i>With 4 brushes</i>	$4 \times 30 \times 30 \times 0.05$	$= 180 \text{ watts.}$
<i>With 2 brushes</i>	$\left\{ \begin{array}{l} 1 \times 90 \times 90 \times 0.05 \\ 3 \times 30 \times 30 \times 0.05 \end{array} \right\}$	$= 270 \text{ watts.}$

It is not an uncommon thing in the case of 6-pole slow-speed exciter machines to see only 4 brush-sets instead of 6.

*Increase in number of Brush-sets.*—In cases where wave-windings are used, requiring, as we have seen, only two brush-sets, it is often advisable to use *more* sets than two. This is particularly the case where the current to be collected is several hundred amperes. In fact, though in one sense only two sets are required, and these situated at an angular distance apart equal to the angular distance from one N-pole to any S-pole, there is no harm done if as many sets are employed as there are poles. Consider a singly re-entrant simplex wave-winding for an 8-pole machine such as Fig. 31. Whenever any brush

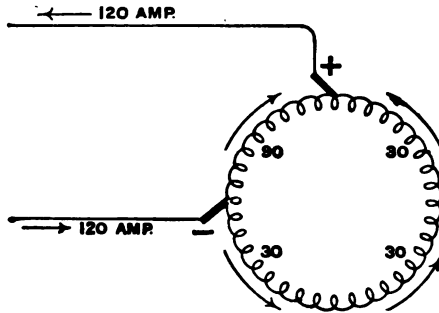


FIG. 44.

bridges across between two adjacent bars of the commutator it short-circuits one "round" of the wave-winding, and this "round" is connected at three intermediate points to other bars of the commutator. So, if the short-circuiting brush is a + brush, no harm will be done by three other + brushes touching at the other points. If these other brushes are broad enough to bridge across two commutator bars, then they may have the effect that commutation may go on at them also, three "rounds" instead of one undergoing commutation together. Or, what amounts to the same thing, the duration of act of commutation for any one "round" will be prolonged, much as it would be if for the one brush there were simply substituted one of greater

breadth. Certain it is that the commutation is in general improved by using more brush-sets than two. Many makers of multipolar machines with wave-windings, habitually use the full number all round the commutator. As examples, see the Kolben 10-pole machine, p. 216 and the Oerlikon 12-pole machine, p. 188.

*Choice of Number of Circuits.*—From the considerations already discussed it will be seen that it is possible to have windings that give any desired (even) number of circuits in machines having any number of poles. It was not known until recent years that this could be so; that, for example, one might have a 6-pole machine with 4 circuits, or an 8-pole machine with 6 circuits. A few considerations on the choice of alternatives may be desirable. In large multipolar generators it is as a rule inadvisable to have more than 100 or 150 amperes in any one circuit. [Special machines for electro-chemical work form exceptions.] Suppose then it were desired to design a 6-pole machine to give an output of 400 amperes. If designed with 2 circuits as a singly re-entrant wave-winding, there would be 200 amperes per circuit. If with a duplex singly re-entrant wave-winding, or a simplex doubly re-entrant wave-winding, there would be 4 circuits each carrying 100 amperes. If with a triplex singly re-entrant wave-winding, or with a parallel lap-winding, 6 circuits with  $66\cdot6$  amperes each. In each case except the last there might be only 2 brush-sets; but in each case 6 brush-sets would be preferable. From this last point of view there is nothing to choose. But the 2-circuit winding is too thick, and the 6-circuit winding involves an unnecessarily great number of conductors and connexions. The 4-circuit winding is distinctly preferable. Again suppose a 12-pole slow-speed machine were desired for a high voltage and to give out 300 amperes. A parallel winding with 12 circuits each carrying only 25 amperes would be absurd: a 2-circuit would be distinctly preferable.

Thus it will be seen that wave-windings, with their many possibilities of different groupings in series, series-parallel, etc., offer distinct advantages over lap-windings, and they possess the further incidental advantages of equalizing any inequality

in the magnetic fields of the various poles, and, in general, of requiring fewer conductors and end-connexions than lap-windings do. Arnold has given the following very striking example of the adaptations of wave-winding:—

Taking the formula (p. 96) for series parallel grouping  $y_k = \frac{2 K \pm c}{p}$ , and applying it to the case of a 6-pole machine with 290 conductors and 145 commutator bars, we may have, with one and the same size of core-disk, and the same size of conductors, the following cases:—

No. of circuits.	Winding Step at Commutator.	Volts.	Amperes.
2	48	250	100
4	49	125	200
8	47	62·5	400
10	50	50	500

With the same core-disk, a doubly re-entrant lap-winding would give:—

12	2	43	600
----	---	----	-----

A disadvantage of series-groupings is, that in general they require an odd number of slots, making construction of the disks in segments a not too easy matter, unless the number of slots is divisible by 9, 15, or 21. Some makers find commutation less satisfactory in these machines than in those with parallel grouping.

*Equalizing Connexions.*—It was noted above, that if for any reason the poles are of unequal strength, parallel-windings, whether lap-wound or ring-wound, work unequally, the current no longer dividing itself equally between the various circuits that are in parallel. As a result the heating is no longer a minimum. To mitigate this evil it is now customary to provide parallel-wound armatures with *equalizing connexions*, which are cross-connexions between those parts of the winding which are, or ought to be, at equal potentials.

As a matter of history such cross-connexions were introduced many years ago for other reasons.

Such cross-connexions will obviously have the tendency to .

equalize the amounts of current collected at the various sets of brushes. In multipolar machines, any two or more points in the winding that are during the rotation at nearly equal potentials may be connected together. If there were perfect symmetry in the field system no currents would flow along such connectors; but, owing to imperfect symmetry the induction in the various sections of the winding may be unequal and the



FIG. 45.—ARMATURE WITH EQUALIZING RINGS.

currents not equally distributed. Thus in a 10-pole machine with parallel winding, suppose two of the poles to be badly excited owing to some defect of the exciting bobbins, then the sections of the armature winding as they pass those poles will not generate the full electromotive force, and at this instant there will be an abnormal amount of current drawn from the other sections, tending to set up sparking. If now there are chosen 5 equidistant points on the winding and these are joined

together by a connexion of low resistance, by being united to a copper ring, this adjunct will, at those instants when these five points are near the commutation-points, tend to equalize the distribution of current. But to be effective several such equalizing rings are needed, each independent of the other, and each connected down to the winding at points spaced out at distances apart equal to twice the pole-pitch.

As an example, suppose a 10-pole machine having  $Z = 480$ , with a parallel lap-winding, and that we decide to have 8 equalizing rings. As there are 96 conductors within the double-pole pitch any conductor (No. 1 for example) will be joined to the 96th, beyond it, and so on around the first ring. As there are to be 8 rings, if the first ring is joined to conductor No. 1, the next ring must be joined to the conductor that is the eighth part of the distance along the winding from No. 1 towards No. 97, that is to a conductor 12 places further on, namely No. 13. and so forth. Then the connexions to the rings may be tabulated like a winding-table as follows:

First ring . . . .	1	97	193	289	385
Second ring . . .	13	109	205	301	397
Third ring . . .	25	121	217	313	409
Fourth ring . . .	37	133	229	325	421
Fifth ring . . . .	49	145	241	337	433
Sixth ring . . . .	61	157	253	349	445
Seventh ring . . .	73	169	265	361	457
Eighth ring . . . .	85	181	277	373	469

It will be obvious that it is expedient for perfect symmetry that in designing an armature to be furnished with equalizing rings,  $Z$  should be chosen such that the number of rings and the number of poles are both of them factors of  $Z$ . In the case of double-current machines (see as example, Fig. 73) with connexions to yield three-phase currents, such three-phase connectors serve as equalizers even though no three-phase current is being drawn from the armature. Fig. 45 shows such equalizing rings in an armature of the Thomson-Houston Co. They

are sometimes arranged at the back of the armature (see the machine of the English Electric Company, Fig. 82), or sometimes inside the commutator, or at the back of it (see the Scott and Mountain machine, Fig. 69). In some cases they are placed over the armature periphery like binding wires. The theory of equalizing connexions has been treated very fully by Arnold.<sup>1</sup> In order to discuss the application of equalizing connexions to wave-windings he has suggested an ingenious "reduced scheme" or diagram in which he takes the various numbered sections of a wave-winding and rearranges them like a two-pole ring winding having equivalent properties. This is best understood by comparing Figs. 34 to 39, each of which represents a wave-winding together with the "reduced diagram" of the same winding. When such diagrams are made for 4-circuit or 6-circuit windings, it at once becomes obvious which coils are or ought to be equipotential, and the points to be joined by equalizing connexions can be seen. Arnold has patented equalizing connexions in wave-windings. One difficulty, namely that wave-windings require odd numbers of slots, giving rise to unbalanced groupings that are unsymmetrical, Arnold purposes to obviate by interpolating a single lap in the wave-winding in any section which has one element too few.

To remedy inequality of poles in series windings, Mr. B. G. Lamme, of Pittsburg, has devised<sup>2</sup> the method of laying in the same slots a separate closed winding of low resistance connected down at symmetrical points, like the ordinary equalizing connexions, to two or more insulated rings. This virtually makes a parallel connected two (or more) phase closed winding, in which, unless the inductive actions are unequal, there will be no currents; but in which if the inductive actions of the individual poles are unequal, balancing currents will be induced.

<sup>1</sup> *Elektrotech. Zeitschr.* xxiii., 215-220 and 233-235, 1902; and in his work *Gleichstrom Maschinen* (1902).

<sup>2</sup> U. S. P., No. 646,092.

## CHAPTER VI.

## ESTIMATION OF LOSSES, HEATING, AND PRESSURE-DROP.

IN this chapter we propose to consider these questions from the designer's point of view, as they are leading features of any design and require to be accurately predetermined from the drawings. On account of the diminishing importance of bipolar machines and of those with smooth core armatures, we shall consider, both in this chapter and the next (which deals with the design of continuous-current machines), the case more particularly of multipolar machines and machines with slotted armatures.

The losses occurring in any dynamo or motor come under six heads, as follows:—

A. *Copper Losses*.—These consist of the sum of the  $C^2R$  losses in armature and series coils (if any) and increase with the load, but are independent of the speed.

B. *Iron Losses*.—These are made up of the eddy-current and hysteresis losses produced in the armature core-plates owing to the changes of flux-density to which they are subjected in each revolution. They vary slightly with the load, and are always variable with the speed. There are also certain losses in the case of machines with toothed armatures due to the production of eddy-currents in the pole-pieces.

C. *Excitation Losses*, that is, the watts expended in heat, in driving the magnetizing current around the magnetizing coils; which losses must be debited against the dynamo, as they lessen the efficiency.

D. *Commutator Losses*.—These consist of—

- (1)  $C^2R$  loss on account of contact resistance.
- (2) Brush friction loss.

(3) Losses through sparking, and through eddy-currents in the commutator bars.

Of these, Nos. (1) and (2) are as a rule the only ones necessary to consider. There are also local circuits in the brushes producing a small loss of energy.

E. *Friction and Windage Losses*.—The former is the loss due to friction of bearings, which depends only upon the load. The latter is the loss occasioned by the armature churning the air. It is independent of the load but varying with speed.

F. *Secondary Copper Losses*.—We will consider these separately.

(A.) *Copper Losses*.

Let  $w_c$  represent the total copper loss of the machine.

" $r_a$	"	(hot) resistance of the armature.
" $r_m$	"	" " " series coils.
" $C_a$	"	full-load armature current.
" $l$	"	total length of armature conductor in feet, including end connectors.
" $s$	"	section of the armature conductor in sq. inches.

Then we have for the total resistance of the conductors on the armature, considered as all in series irrespective of their grouping,

$$r = \left[ 0.000008 \times \left\{ 1 + 0.004 (t - 15) \right\} \frac{l}{s} \right]$$

at a temperature of  $t^\circ$  C. This formula becomes at temperatures of about  $60^\circ$  C. (compare p. 42),

$$r = \frac{9.5 \times l}{10^6 \times s}.$$

The actual resistance proper of the armature  $r$  depends on the form of winding employed, and the number of circuits in parallel from brush to brush, the rules for which are given on p. 97. For all bipolar machines and simple series-connected multipolar armatures, with two circuits only, the rule becomes

$$r_a = r \div 4.$$

For simple multipolar parallel-connected armatures running in fields of  $p$  poles, we have

$$r_a = r \div p^2,$$

because there are as many circuits as poles.

Then the copper loss of the machine is

$$w_c = (C_a^2 \times r_a) + (C_m^2 \times r_m).$$

(B.) *Iron Losses*.—For the calculation of the hysteresis loss, we can either make use of the formula given on p. 9, or, better still, refer to a curve obtained by test upon the actual iron. Such a curve is shown in Fig. 2, the ordinates giving directly the watts lost per pound of iron at the different flux-densities given by the abscissæ, and at 30 periods per second. To find then the hysteresis loss in a slotted armature, for instance, we proceed as follows. First, calculate the number of complete magnetic reversals, thus

$$f = \frac{1}{2} \frac{\text{revs. per min.}}{60} \times p;$$

where  $f$  is the frequency,  $p$  the number of field-poles. Next calculate the actual flux-densities  $B_t$  and  $B_c$  in teeth and armature core respectively. A reference to the upper curve of Fig. 2 will give the corresponding number of watts lost per pound of iron at these flux-densities. Multiplying the two numbers so obtained by the total weight of the iron in teeth and core, and adding the two results, we obtain the hysteresis loss in the armature at  $f = 30$  periods per second. If the frequency of reversal is either higher or lower than this, the hysteresis loss will be proportionately greater or less. Instead of computing these losses from the weight of the iron we may compute them from the volume (cubic inches) by the curves given in Fig. 3 on p. 13, or estimate it from Table III., p. 12.

The eddy-current losses are proportional to the square of the flux-density, to the square of the frequency, and to the

square of the thickness of the armature plate. They may be calculated from the formula (see p. 12),

$$\text{Watts lost per cub. inch} = (40.64 \times t^2 \times f^2 \times B^2) 10^{-12},$$

where  $t$  represents the thickness of plate in inches. As, however, this formula takes no account of the short-circuiting of individual plates caused by the machining of the armature, the results given by the formula will always be found to be too small. The error is partly compensated for by the fact that the formula is based upon the specific resistance of iron at  $0^\circ \text{C.}$ , and as the armature will always be fairly hot, the increase of resistance will diminish the eddy-current loss. But a reference to the lower curve of Fig. 2, p. 10, will usually give good results, and it is easier to apply as it gives directly the eddy-current loss per pound at different flux-densities for the standard thickness of English armature plate, viz. 25 mils, and for 30 periods per second. It contains a correction-factor to cover the loss due to the after-tooling of the core, but should the frequency (or thickness of plate) be greater or less than the one for which the curve was plotted, the final result must be raised or lowered in proportion to the square of the frequency or plate-thickness. Table IV. on p. 14 and the curves of Fig. 3 on p. 15 are also useful.

We have assumed above that the volume of active iron is the same as the actual volume of iron in the armature. This is of course not strictly true, as some of the teeth and perhaps a small portion of the core may be missed by the flux going from pole to pole. The error is, however, negligible, and is on the right side. It tends to correct for the eddy-current loss in the pole-faces, which is impossible to calculate. The iron loss of the armature is hence

$$w_t = w_e + w_h,$$

where  $w_e$  and  $w_h$  are the eddy-current and hysteresis losses respectively, evaluated separately as above.

(C.) *Excitation Losses.*—If  $r_m$  is the resistance (hot) of the shunt winding, calculated by means of one of the resistance formulæ already given, and  $V$  the electromotive-force at its

terminals at full load, we have  $\left(\frac{V}{r_m} \times V\right) = \frac{V^2}{r_m}$  as the watts actually used in excitation. To these must be added the loss in the shunt regulating resistance, if any, giving a total loss of  $w_x$  watts at full load. The watts required for excitation purposes by shunt machines vary in practice from one to ten per cent. of the output, according to the size of machine. As a guide to the designer in this direction, the table below may be useful.

Output of machine in kilowatts.	Excitation loss in percent. of full load output.
5	6
10	5
20	4
30	3.5
50	3
100	2.75
200	2.5
300	2.25
500	2.0
1000	1.75
2000	1.5

(D.) *Commutator Losses.*—The contact resistance between commutator and brushes depends mainly upon (1) the material of the brush; (2) the bearing pressure; (3) the peripheral speed of the commutator; and (4) the current-density in the brush. Other causes, such as the condition of commutator and brushes, weight and spring of the brush-holders, etc., will also influence the contact resistance to a greater or less extent.

Carbon brushes are worked in practice at current-densities of about 40 amperes per square inch for machines of medium and large output. For small machines this figure may be considerably exceeded, but the maximum permissible figure is 80 amperes per square inch. Copper brushes are generally worked

at 150 to 200 amperes per square inch, and sometimes even higher for small machines. The bearing pressures found in actual machines are 1·25 to 1·5 lb. per square inch for copper brushes, and 1·5 to 2 lb. per square inch for carbon brushes, this figure being exceeded for tramway motors on account of vibration. Peripheral commutator speeds vary from 1500 to 2500 feet per minute according to size of machine. The latter figure is occasionally exceeded with large tramway generators. Hobart uses sometimes 3000 feet per minute.

Recent tests made by Professor Arnold<sup>1</sup> upon commutator losses show that both for carbon and copper brushes, the contact resistance decreases rapidly with increasing current density relatively to the peripheral speeds, it being more marked in the case of carbon. According to his experiments the contact resistance of carbon brushes for current-densities of 50 to 30 amperes per square inch and peripheral speeds of 1200 to 2400 feet per minute may be taken as being 0·023 to 0·039 ohm per square inch of contact. For copper brushes the corresponding values may be taken as being 0·00077 to 0·0023 ohm per square inch. So that we can safely assume as outside values of the contact resistance per square inch

For carbon brushes	.	.	0·04 ohm.
“ copper “	.	.	0·003 ohm.

These values enabling us to easily calculate the commutator loss brought about by contact resistance for any machine.

*Example.*—In a large electro-metallurgical dynamo by Brown with an output of 4000 amperes, there are about 160 square inches of brush contact surface, or 80 square inches for entry and 80 for exit of the current, collecting about 50 amperes per square inch. Assuming the contact resistance at 0·02 ohm per square inch we find the whole C<sup>2</sup>R loss will be

$$2 \times 4000 \times 4000 \times \frac{0\cdot02}{80} = 8000 \text{ watts.}$$

The contact resistance is not constant, but varies approximately inversely as the current density; thus, with 1·5 lb. per

<sup>1</sup> See *Elektrotechnische Zeitschrift*, No. 1, 1899.

square inch pressure the resistance is about 0.04 when the current density is 20 amperes to the square inch, and goes down to about 0.02 when the density is 40 amperes to the square inch. Hence it follows, that the drop of potential due to this contact resistance is nearly constant at all loads, and may be taken at from 0.8 to 1.0 volt at each side, positive and negative of the commutator, or from 1.6 to 2 volts on the whole machine.

The loss arising through the friction of the brushes against the rotating commutator depends upon the bearing pressure of the brushes, the peripheral speed of the commutator, and the *coefficient of friction* between the two. If brushes and commutator are in good condition this latter may be taken as

For carbon brushes	.	.	0.3
" copper "	.	.	0.2

In order then to calculate the watts lost through brush friction, we simply multiply the total pressure on the commutator (in pounds) by the peripheral speed in feet per minute and by the friction coefficient, which gives the losses in foot-pounds per minute, and then reduce to watts by dividing by 33,000 and multiplying by 746. Or, since  $\frac{746}{33000} = 0.0226$  the foot-pounds per minute may be brought to watts by multiplying by this figure, or by dividing by 44.2, which is its reciprocal.

*Example.*—Taking as example the same machine, if we assume the brush pressure as 1.55 lbs. per square inch, and the friction coefficient as 0.3, since the peripheral speed of the commutator is 3350 feet per minute, we have as the friction loss

$$160 \times 1.55 \times 0.3 \times 3350 \times 746 \div 33,000 = 5650 \text{ watts.}$$

In estimating commutator-losses it must be borne carefully in mind that with brushes or commutator in bad condition, the losses (both mechanical and electrical) will probably come out considerably greater than the above calculations indicate.

*Commutator Heating.*

Let  $w_b$  represent the total commutator loss, electrical and mechanical, in watts.

“  $S_s$  represent the heat radiating surface of commutator in square inches.

“  $v$  represent the peripheral speed of the commutator in feet per minute.

“  $\theta_c$  represent the final temperature rise, in degrees Centigrade.

Then, according to tests made by Professor E. Arnold,

$$\theta = \frac{46.5 \times w_b}{S_s (1 + .0005 v)}.$$

According to Messrs. Parshall and Hobart, the rise of temperature of the commutator will seldom exceed  $20^\circ$  C. per watt per square inch of peripheral radiating surface at a peripheral speed of 2500 feet per minute; for ventilated commutators this figure may be considerably improved upon.

(E) *Friction and Windage Losses.*—These are naturally very difficult, if not impossible, to calculate with any accuracy, and are usually estimated by the designer from previous experience of the same type of machine as a percentage of the full-load output. Direct-coupled machines will have smaller friction losses than belt or rope-driven machines, and low speed dynamos smaller mechanical losses than high-speed machines of the same output. For belt- or rope-driven machines running at the usual speeds found in practice, the mechanical losses may be taken as being from 3 to 1 per cent. for outputs of 10 to 300 kilowatts. For an approximate method of calculating the mechanical losses of dynamos, the reader should consult the writings of Mr. Fischer-Hinnen. *Continuous Current Dynamos*, London, 1899.

*Efficiency.*—Having estimated the separate losses, it becomes a very simple matter to calculate the efficiency of the machine for the load at which the calculations were made. By the efficiency we mean simply the relation between the power actually delivered electrically at the terminals of the

dynamo to the mains, and the power applied mechanically at the shaft to turn the armature, both qualities being for convenience expressed in watts, so that we may write the efficiency as

$$\frac{\text{Output watts}}{\text{Input watts}} = \eta.$$

There is little advantage in adhering to the old terms "electrical efficiency," "gross efficiency," etc., as the above definition includes everything within the true use of the term. If  $W$  is the output in watts of the dynamo or motor, and  $w$  the sum of all its losses as estimated above, we have

$$\eta = \frac{W}{W + w} \times 100$$

as the true or commercial efficiency expressed as a percentage. The efficiency will differ at different loads, since the watts lost constitute a different proportion at different outputs. The core-losses are nearly constant at all loads, and so is the loss of energy due to excitation by the shunt coils. The question what the efficiency will be at  $\frac{1}{2}$ -load, or  $\frac{1}{4}$ -load, or at  $1\frac{1}{4}$  load depends largely on the proportion of the various losses. At no-load there are hysteresis and eddy-currents in the iron core-body, excitation losses, and friction. As the load increases there is added the loss by heating in the copper of the armature, and in the series coils; and these losses increase with the square of the current. Consequently the efficiency, which at no-load is zero, goes up to a certain maximum, which, if the design is good, should be at the normal full-load; but it should be high also at half-load and even at one quarter-load.

The form of the efficiency curve is shown by a typical example in Fig. 46, which also shows the values of the separate losses at different loads. This set of curves relates to a particular 6-pole 200 kilowatt machine, supplied by the General Electric Company to the Central London Railway and described by Messrs. Parshall and Hobart.<sup>1</sup> Fig. 47 shows how

<sup>1</sup> *Electric Generators*, p. 190.

the excitation in this same machine automatically increases with the load by the compounding action of the series coil.

### 3 Secondary Copper Losses.

In addition to the ordinary ohmic loss of power due to the resistance of the armature conductors, there are certain obscure

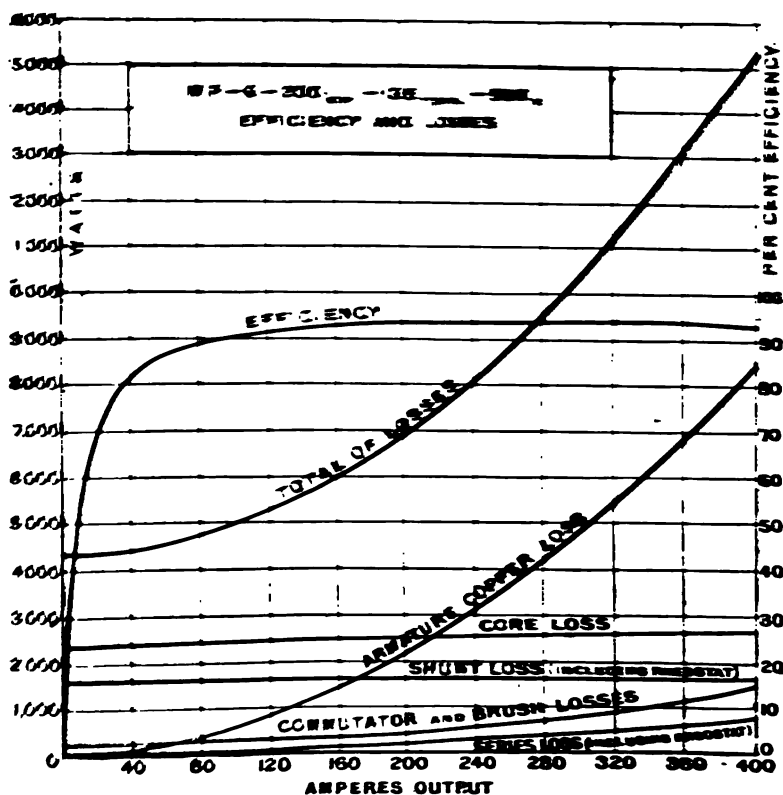


FIG. 46.

causes of loss that lower the measured efficiency of machines. One of these is the production of eddy-currents in pole-pieces, heating them and wasting some of the power applied to drive

the armature. Another is the production of eddy-currents in the copper conductors themselves. Akin to this is the actual increase of resistance which occurs if for any reason the current

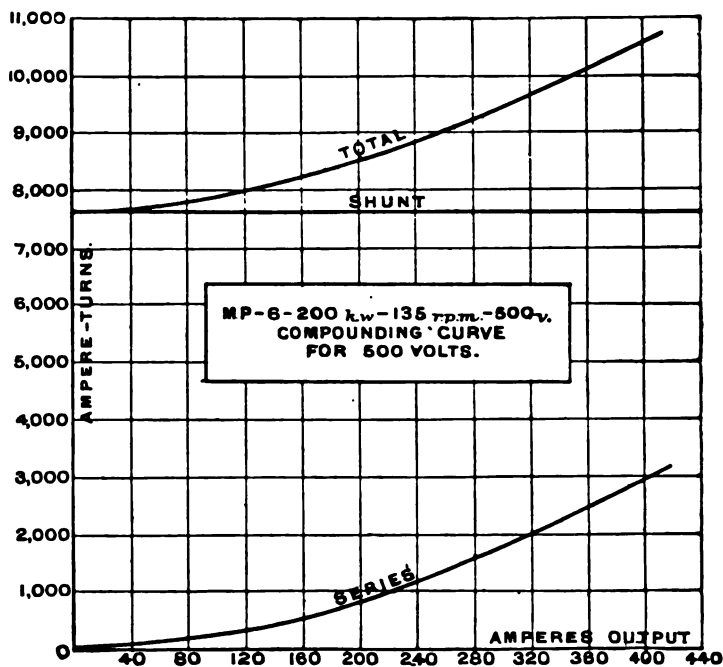


FIG. 47.

in the conductor does not distribute itself equably in the cross-section. This may (and does) occur in the following manner.

For bar-armatures, rectangular bars set edgewise in slots are almost universal. Round bars are very rarely found in continuous-current machines. Smooth-core armatures do not lend themselves to bar-winding, because solid copper bars set on the outside of a smooth-core are liable to a serious waste of energy that does not occur in small-wire windings. When the conductors present any considerable breadth, there is a tendency to set up eddy-currents in them as they enter or leave the magnetic field, owing to the fact that one edge of the bar may be passing through a field the density of which is very

different from that of the field through which the other edge is passing. For example, if the surface speed is 3000 feet per minute, and the bars are  $\frac{1}{2}$  inch wide, it may be that the front edge may be in a field of density, say, of 40,000 lines per square inch, while the other edge is one of 30,000 only. If the active length of the conductor is, say, 12 inches, then its front edge will be cutting magnetic lines at the rate of 288,000,000 lines per second, and therefore the induction in that edge will be 2.88 volts; while in the hind edge the corresponding induction will be only 2.16 volts. The difference, or 0.72 volts, will tend to set up an eddy-current flowing up one edge and down the other edge of the bar. Suppose the bar to be  $\frac{1}{2}$  inch thick: if for the purpose of argument it is regarded as equivalent to two parallel bars  $\frac{1}{4}$  thick and  $\frac{1}{4}$  wide united at the ends, the resistance round this elongated loop will be that of a rod of copper 24 inches long and of  $0.25 \times 0.125$  square inches of cross-section. At 60° C. this resistance will be only 0.000607

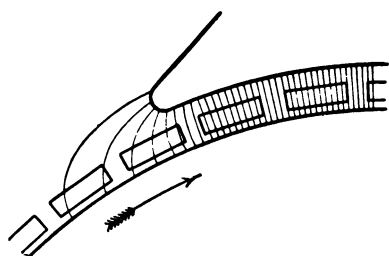


FIG. 48.—UNEQUAL INDUCTION IN EDGES OF FLAT BAR.

ohm; and an electromotive-force of 0.72 volts would set up a current of 1186 amperes! But as the electromotive-force is 0.72 between the extreme edges only and has lesser values towards the middle of the width, the eddy-current up and down the strip will be less than this. Even if one

takes a twentieth part of the value so found as being more probable it is serious enough from the heating and waste of power that it entails; for at no-load there would be this waste in each conductor as it approached and left each pole. At full-load there might be no actual eddy-current. For if the full load current through the conductor were 150 amperes, then superposing upon this an eddy-current of 59 amperes in the two halves of the conductor (as in Fig. 49), the result would be that in one half of it the current would be  $75 + 59 = 134$  am-

peres, and in the other half  $75 - 59 = 16$  amperes. The 150 amperes no longer distribute themselves equally through the breadth of the strip; and the total heating of the strip would

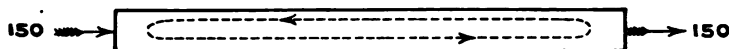


FIG. 49.—EDDY-CURRENT IN WIDE BAR.

be precisely the same as if the eddy-current were really there. At the peripheral speeds actually used, it is found impossible by any shaping of the pole corners to avoid excessive heating of solid copper bars on a smooth core if their width exceeds 0.2 inch.

In sunk windings these losses practically do not occur, unless the slots are very narrow and deep so that there is a magnetic leakage across the slot from tooth to tooth. In the case of a conductor being made up of several wires in parallel, the separate wires must not lie in different slots, for reasons similar to those already discussed.

To eliminate such eddy-current losses Crompton<sup>1</sup> proposed several methods of twisting or imbricating around one another two or more strips, so as more effectually to neutralise the eddy-currents. He introduced the use of bars made of stranded wire compressed into a rectangular form, each wire being oxidized or lightly insulated.

*Calculation of the Pressure-Drop.*—It was shown in Chapter I. (page 37) how the saturation curve of a dynamo machine may be constructed, that is, the curve connecting the ampere-turns upon the magnetic circuit and the useful flux produced by them in the air-gap. Let  $OC$  in Fig. 50 represent such a *saturation curve*, the ordinates representing the flux being cut by the conductors and the abscissæ the ampere-turns producing it. Now the fundamental equation for the induced electromotive-force (page 79) tells us that

$$E = \frac{\phi}{c} n Z N_a \div 10^8,$$

or that  $E = N_a \times$  a constant depending upon the construction and operation of the machine, and which may be denoted by  $j$ .

<sup>1</sup> See *Jour. Inst. Elec. Engineers*, xix. 240, 1890.

Consequently the ordinates of the curve represent the induced electromotive-force to a different scale, that is,  $E = j N_a$ , and we may therefore regard it as being the curve of induced electromotive-force of the machine for different excitations at constant speed—in other words, it is the “no-load characteristic” of the machine. Assuming then that Fig. 50 represents this curve for a particular machine, we can see from it what the pressure-drop at constant speed and excitation will be, and incidentally determine the amount of compounding that must be employed in order that constant pressure may be maintained at the ter-

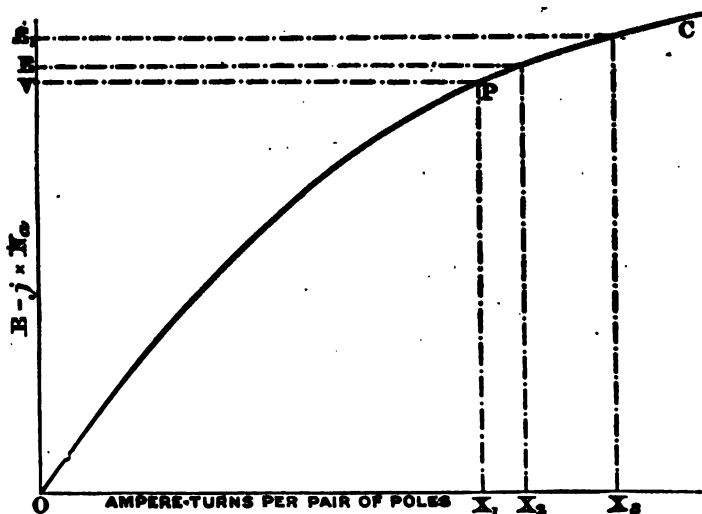


FIG. 50.—SATURATION CURVE.

minals of the load. Let the ordinate  $O V$  represent this constant pressure. Evidently at no load an excitation of  $X_1$  ampere-turns are required. Now at the full load of  $C_a$  amperes, there will be three causes tending to lower the pressure, namely the effects of (a) ohmic resistance of armature and series coils; (b) demagnetizing action of the armature; and (c) distortion of the armature flux, the effect of which only becomes of importance in slotted armatures. The first two are easily allowed for. The lost volts at full load are evidently

$$e = (C_a \times r_a) + (C_a \times r_s),$$

the last term not being required in the case of shunt machines. Adding this quantity to the ordinate  $O V$  we obtain  $O E$  as the pressure that must actually be generated in the armature, and this requires an excitation of  $X_2$  ampere-turns. As it is frequently convenient to check the dimensions of an armature conductor in a preliminary design by means of this quantity, the table appended below, giving average values of  $e$ , may be of use in this direction.

Output of the machine in kilowatts.	Lost volts as a percentage of full-load pressure.	
	Shunt machines.	Compound machines.
5	7	10
10	6	8
25	5	7
50	4	6
100	$3\frac{1}{2}$	5
200	3	4
500	$2\frac{1}{2}$	3
1000	2	$2\frac{1}{2}$
2000	$1\frac{1}{2}$	2

With regard to the demagnetizing ampere-turns of the armature, we know generally that these are the ampere-turns lying in the angle of brush lead. Assuming that the brushes will be set just under the pole-tips at full load, the demagnetizing turns are given by *number of conductors lying between the adjacent pole corners multiplied by the current in them*.

These ampere-turns we multiply by the dispersion co-efficient  $\nu$ , because they have to be neutralized on the field system, then add the result to  $X_2$ , and set them off as  $X_3$ ; and by projecting this value up to the curve and across, find the point  $E_1$ .

Now with a smooth core armature, the distortion of the flux in the air-gap does not produce a pressure-drop. In Fig. 51 let  $A B$  represent the width of the pole-face to scale, and  $E F$  the flux-density in the air-gap  $B_3$ . Then the area  $A B C D$

is proportional to the useful flux  $N_a$ , and at no-load we may regard this flux as being distributed uniformly along the air-gap as indicated by the rectangle. But at full-load the flux is heaped up at the forward pole-horn and withdrawn from the hindward horn, as indicated by the figure A H G B, and as the permeability of the air-gap is constant, the area of this figure is equal to the area of the rectangle A B C D. For instance, if  $X_g$  are the ampere-turns required for the air-gap (flux-density =  $B_a$ ), and  $X_t$  are the ampere-turns lying under the poles and producing the distortion, we have

$$\begin{array}{lll} \text{Line F E} & \text{proportional to} & X_g; \\ \text{" A H} & \text{"} & X_g - X_d; \\ \text{" B G} & \text{"} & X_g + X_d; \end{array}$$

and consequently no diminution of the total flux takes place in a smooth core armature.

We see then that Fig. 50 gives us the compounding for a machine with such an armature. We see that if the load were

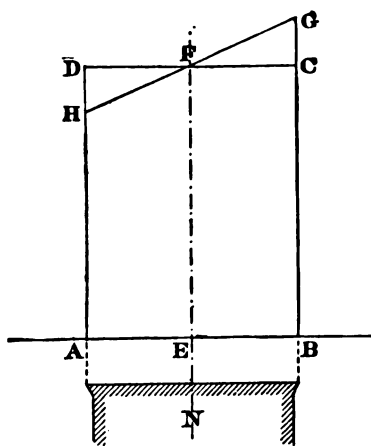


FIG. 51.

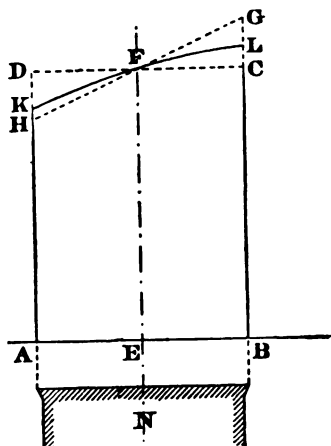


FIG. 52.

switched off (the speed remaining the same) the volts at the terminals of the machine would rise from the value  $O V$  to that of  $O E_1$ . Consequently the compounding ampere-turns are given by  $(X_3 - X_1)$ , and the shunt ampere-turns by  $X_1$ . If

the machine were merely shunt-wound, it would require to have inserted in the shunt-circuit a regulating rheostat which could be adjusted to give  $X_1$  ampere-turns at no-load, and  $X_3$  ampere-turns at full-load.

But for toothed armature machines there must be made an allowance for the distorting effect, due to the fact that the permeability of the teeth is not constant. As before, let (in Fig. 52) the rectangle A B C D be proportional to the useful flux, E F representing the flux-density  $B_s$  in the air-gap. If the teeth were of constant permeability, the flux from the pole-face could be regarded as being of the same value as at no-load, but distributed differently, as shown by the figure A B G H. But the increased flux-density at the forward pole-horn causes the permeability of the teeth at this point to have a much lower value than they have with the flux-density  $B_s$ , while, on the other hand, the permeability of the teeth under the hindward horn has increased on account of the diminished flux-density in them. As a result, the line H F G takes a bent form as shown by the curve K L; and *the shape of this curve is the same as that of the saturation curve over this range*. As can readily be seen from the figure, the area A K L B is considerably less than the area A H G B, that is, there is a diminution of the useful flux  $N_a$ , and consequently a corresponding pressure drop, and the diminution will be as a rule greater, the greater the flux-densities in the teeth.

One way of estimating the number of compensating ampere-turns required to overcome the effect produced by the distortion of the useful field is as follows. In Fig. 53 let O L be the saturation curve of the machine, the ampere-turns required for no-load, and for the full-load induced electromotive force on no-load (and, therefore, without the extra allowance for distortion), being set off upon its scale of abscissæ O X as  $X_1$  and  $X_3$  respectively, these being estimated as shown above. Now mark off

$$O A = X_3 - X_a; O B = X_3 + X_a$$

upon O X. The point A then represents the hindward pole-horn, and point B the forward pole-horn. Had distortion been

absent, the ampere-turns required to produce  $E_1$  volts would have produced a flux across the gap proportional to the flux is proportional to the smaller area  $A B L K$ . All we have to do now is to shift the point  $F$  higher up the curve to the area of the piece  $A B C D$ . But as distortion is present, a point such as  $F'$ , so that the area  $A' B' L' K'$  becomes equal to the area  $A B C D$ . This gives a new point  $X_4$  along  $O X$ , representing the full load ampere-turns required. Consequently, we see that,

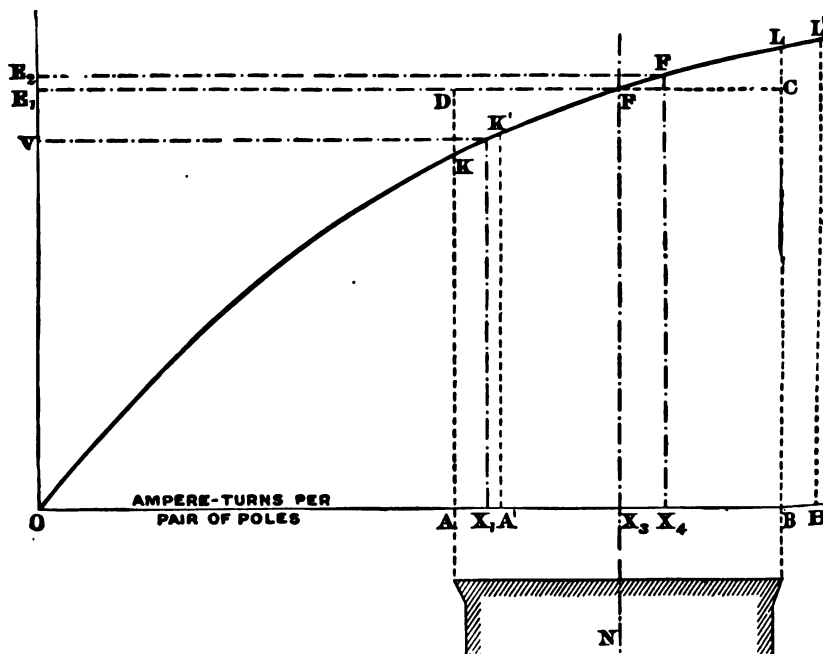


FIG. 53.

if the machine is compound-wound, the series ampere-turns must be  $X_4 - X_1$ , and the shunt-turns  $X_1$  in order that the terminal volts may be  $O V$  at full load. If a shunt machine, the resistance of the shunt rheostat must be capable of reducing  $X_4$  ampere-turns to  $X_1$  ampere-turns. If the machine had no shunt resistance, then the drop from full-load to no-load would be  $(O E_2 - O V)$  at constant speed.

It is unnecessary to say that the above methods of prede-

termining the pressure-drop and amount of compounding will not give an exact result. Such a result would be quite impossible to arrive at by any process of calculation only, and as a matter of fact great accuracy is not required. If the machine is shunt-wound, the regulating rheostat will in practice have sufficient margin each way to cover the inaccuracy, while compound windings are in practice adjusted in the test-room by the method of experiment. It becomes, therefore, necessary only to predetermine the pressure-drop from the point of view of the winding space required on the magnet bobbins, and from

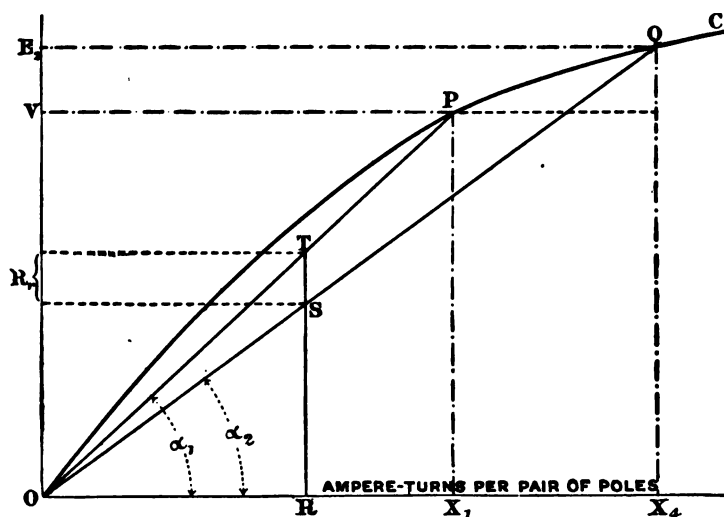


FIG. 54.

this point of view the above method will be found to give extremely good results.

*Resistance of Shunt Regulator.*—Knowing the values of  $X_1$  and  $X_4$  as found above ( $X_1$  and  $X_3$  for machines having smooth core-armatures) it is a simple matter to determine the necessary resistance for the shunt regulator. Let, in Fig. 54,  $OC$  be the no-load curve of the machine, the no-load and full-load ampere-turns being given by  $X_1$  and  $X_4$ , respectively. Then we have to find the value of shunt regulating resistance in order that the machine may deliver current at the constant

electromotive-force  $O V$ ; it being assumed that the regulator is to be short-circuited at full-load. First, obtain the points  $P$  and  $Q$  by projection, and join  $O P$  and  $O Q$ .

Let the number of shunt turns be denoted by  $S_s$ .

Then shunt current at no-load  $= X_1 \div S_s$ ;

and " " " full "  $= X_4 \div S_s$ ; hence

$$r_s = \frac{S_s \times O E}{X_1} = \tan a_s,$$

$$r_s + r_r = \frac{S_s \times O E}{X_4} = \tan a_r.$$

Along  $O X$  mark off a piece  $O R$  equal to the number of shunt turns  $S_s$ , and to the same scale as  $X_1$  and  $X_4$ , etc. Erect a perpendicular  $R T$ . Then

$$\frac{r_s}{r_s + r_r} = \frac{R S}{R T}.$$

That is  $(R T - R S)$  gives directly the value of  $r_r$  in ohms; it being read off from the scale of electromotive-force, as indicated by the figure.

*The Adjusting Shunt.*—To adjust the operation of compounding coils, they are often shunted with an iron resistance. As the load rises this shunt heats, and its resistance rises relatively to the compounding coils of copper, so increasing the compounding at the maximum load.

On the opposite page, Table X gives a list of suitable materials for rheostats, and the respective coefficients for calculating the lengths required for giving prescribed amounts of resistance.

*Inherent Regulation.*—One way of considering the regulating properties of a machine, is to observe by experiment (or calculate from the saturation curve) how many volts the potential will rise if, being excited with the full ampere-turns necessary to give no-load voltage at the terminals under full-load, the excitation is maintained, but the load taken off the armature. The resulting rise of voltage may be called the *inherent regulation*, as distinguished from the *pressure-drop*.

TABLE X.—RESISTANCE MATERIALS FOR RHEOSTATS.

Name of Material.	Specific Resistance at 0° C.		Temperature Coefficient of Increase Resistance per degree C.	Specific Gravity.	Coefficient to multiply into Copper Conductor of same dimensions to find resistance.
	Microhms per centim cube.	Microhms per inch cube.			
Constantan . .	50	19·7	zero or negative	8·8	30·8
German silver. {	20·9	8·2	0·00044	8·5	13
	30	11·8	0·00036	8·5	18·5
Iron . . . . {	10	3·94	0·00450	7·8	6·2
	12	4·72		7·81	7·4
Kruppin . . .	85	33·5	0·00077	8·8	52·6
Manganese copper	100·6	41·8	0·00004	8·7	62
Manganin . .	46·7	18·4	0·00033	8·94	25
Neusilber . .	37	15·6	0·00020	8·5	23
Nickelin . . {	33·2	13·1	0·00030	9·0	20
	44	17·2	0·00033	9·0	27
Nickel steel . {	29	11·4	0·00050	8·4	18
	75	29·5		8·5	46·5
Platinoid . . {	32·5	12·8	0·00021	8·5	20
	51	20·1		8·7	31
Phosphor-bronze <sup>1</sup>	24·6	9·7	0·00039	8·6	15·2
Rheostan . . . {	47·3	18·6	0·00023	8·6	30
	100	39·4		8·6	62

*N.B.*—The composition of these alloys varies much as to its proportion according to the source of manufacture. For calculating the resistances of wires or strips of these materials, the simplest procedure is to calculate them as if of copper, and then multiply the resistance so found by the coefficient given in the last column of the table. As their specific gravities do not differ greatly from that of copper (8·8) they will all (except iron) weigh approximately the same as a wire of copper of same gauge and length.

<sup>1</sup> Containing 10 per cent. tin.

## CHAPTER VII.

## THE DESIGN OF CONTINUOUS CURRENT DYNAMOS.

THE calculations and formulæ required by the dynamo designer have been already mostly given and explained in the preceding chapters. A careful study of these, and the detailed calculations given of the three representative machines in the present chapter, will make the methods adopted in designing continuous-current dynamos sufficiently clear. Beyond giving a number of working data, and an order of working that may be adopted in designing, we shall rely upon the worked-out examples of the succeeding chapter to give the reader an insight into the principles of dynamo design. It would be useless to do otherwise, as so much depends upon the skill and experience of the designer, the type of the machine, and the conditions of the specification as to speed, output, voltage, regulation, and heating limits to which he is obliged to conform, that no hard-and-fast rules applicable to every case can possibly be given. The following remarks and working constants are to be taken as applying only to modern machines of fair and large sizes—that is, to slotted drum armatures with multipolar field-magnets, which are assumed throughout, except where anything is explicitly said relating to other types.

There are two principal ways of designing a dynamo to fulfil specified conditions as to freedom from sparking, heating and efficiency; the output, speed, and voltage being assumed to be the same in each case. With a given number of poles on the field-magnet frame, and of conductors upon the armature, the effects of armature reaction may be kept down either (1) by working the teeth at normal flux-densities (say 100,000 lines per square inch, and under) and with a wide air-gap, or (2) by

forcing the magnetism of the teeth and working with a smaller air-gap; the high reluctance of the teeth with such large magnetic densities acting like an extension of the air-gap. The former method corresponds to Continental practice, and the latter to American practice in continuous-current dynamo building. It would appear that the second method is considerably the better from the point of view of avoidance of sparking (both being the same with regard to efficiency and heating), and therefore for this reason we adopt it here, as giving a better commercial machine.

There is another aspect in which the plans followed in designing may differ. One may begin by following general experience as to speeds, sizes, and electrical proportions, and having proceeded to sketch out the main features of the design, may then proceed to calculate the power wasted as heat in the various parts, and so estimate the efficiency, and then, after so finding the various items of heat-waste, return and amend the first calculations according as to whether we have found any part to heat too much or too little. Or, instead, one may begin by assuming, as the result of experience, to allot in advance the various permissible losses of power in the various parts—so many watts in the iron core, so many in the armature copper, so many in the field-magnet coils. One will then have a definite idea as to how much cooling surface will be necessary, and what will be the allowable current-densities in the copper and flux-densities in the iron. This procedure settles many points in advance. Similar considerations have long governed the design of transformers, and their advantage has gradually been acknowledged by dynamo designers.

In another respect also dynamo design has developed. Formerly the dynamo designer built his machines without knowing the precise voltage which they would give at any particular speed, and left the speed to be determined by trial after the machine should have been completed; then adding a pulley of such size as would suit the conditions of driving. But nowadays, when nearly all dynamos are direct-driven from engine or turbine, the speed is prescribed beforehand by conditions fixed by the steam-engine builder or the turbine-constructor.

Therefore now all dynamo design proceeds on the supposition of a prescribed speed. Further, in designing a series of dynamos of different outputs from small to large, it must be remembered that engine-conditions govern the selection of speeds, and that it will not do to assume that a 1000-kilowatt dynamo can run at the same speed as a 10-kilowatt dynamo. Neither will it do to assume that the speed may be varied inversely<sup>1</sup> as the number of kilowatts. A rule more near to practice is that in a series of steam-engines of given type, the speeds vary about inversely to the square root of the capacity. If a 10 horse-power engine runs at 800 revolutions per minute, then an engine of 1000 horse-power will not run at  $\frac{1}{10}$  of the speed, but at about  $\frac{1}{10}$  of the speed, namely 80 revolutions per minute.

#### WORKING CONSTANTS AND TRIAL VALUES.

(a) *Flux-densities*.—As average values for the magnetic densities in the various parts of the machine at full load, we may take:—

Flux-density in—	Lines per square inch.	Material.
<b>Armature body</b> .	60,000	sheet iron or steel stampings.
" <b>teeth</b> .	130,000	"    "
<b>Air-gap</b> .	45,000 to 55,000	air.
<b>Magnet cores</b> .	111,000	cast steel or wrought iron.
" <b>yoke</b> .	{ 70,000 to 100,000 35,000 to 50,000	"    " if of cast iron.

For sparkless commutation, the density in the armature-teeth must not differ very much from the above value. Mr. H. S. Meyer recommends an apparent density of 140,000 to 155,000. The density in the armature core-body should be less, and is determined by the permissible iron-loss.

(b) *Length of Air-gap*.—This should not be less than half

<sup>1</sup> If this might be assumed, the design of a series of dynamos would be much simplified, as Mr. S. H. Short has shown, since then all armatures might be made of same axial length, and all field-magnet poles of same size, the number of them being simply increased, 4, 6, 8, 10, 12 or more, in simple proportion to the required capacity.

the width of a single slot, even with highly saturated teeth. If the slot is partly closed, take three-quarters of the maximum width as a trial value for the length of a single air-gap.

(c) *Number of Poles.*—With such values for flux-density, and air-gap length as taken above, the armature ampere-conductors per pole, at full load, should not much exceed 14000. To get a rough idea of the number of poles required, we simply multiply the total number of the conductors,  $Z$ , around the armature by the full-load current in each, divide the product so obtained by 14000, and take the nearest even integer as the number of poles. But this assumes the number of armature-conductors to be known. Another criterion<sup>1</sup> is the prescribed output of current, since, to avoid sparking troubles, it is wise not to attempt to collect more<sup>2</sup> than 200 amperes at any one row of brushes. As the number of rows of brushes in either the positive or the negative set is equal to the number of pairs of poles, the total number of rows of brushes will be the same as the number of poles. Hence it follows that a trial value as to the proper number of poles can be found by dividing the prescribed full-load current by 100. Thus, if the machine is to give 950 amperes, 10 poles will be adequate. (Special machines, such as electrolytic machines, and very slow-speed exciters to be mounted on the shafts of large alternators, are exceptions.) In general this rule gives too few poles for the smaller sizes, and too many for the larger sizes of dynamo.

<sup>1</sup> Wiener (*Practical Calculation*, 2nd edition, 1902, p. 287a) advises to make the choice of poles depend only on the speed, the object being to limit the number of reversals of magnetization per second in the armature-core, and so keep down the armature iron-losses. He states the number of cycles per second at 10 to 15 in slow-speed machines, increasing to as many as 25 or even 35 in high-speed machines. His rule is equivalent to saying that for slow-speed machines one can find the appropriate number of poles by dividing the number of revolutions per minute into 1200 or 1800, and taking the nearest even integer higher than the quotient. But such a rule leaves out of sight the size of the machine: and it would be absurd to give the same number of poles to a 40-kilowatt and to an 800-kilowatt machine, simply because each of them ran at, say, 120 revolutions per minute. Fischer-Hinnen (*Continuous Current Dynamos*, 1899) recommends 4 poles as appropriate for machines between 6 or 20 kilowatts and 100 or 150 kilowatts; and 6 poles as appropriate up to 200 or 300 kilowatts.

<sup>2</sup> Nevertheless satisfactory machines exist with fewer poles than by this rule; for example, the Berlin generators of the A. E. Gesellschaft, giving 2600 amperes and having only 18 poles, and the 6-pole generators of the Oerlikon Company, at the Volta Company in Rome, giving 1500 amperes.

(d) *Current Densities*.—As an approximate guide to the sizes of the conductors required for the different parts, we may take:—

Current Densities.	Amperes per Square Inch.	Square Mils per Ampere.	Circular Mils per Ampere.
In armature conductors . . . {	1500 to 2000	667 500	847 637
In commutator risers . . . {	2400 to 4000	417 250	531 318
In field-magnet coils . . . {	600 to 800	1670 1250	2126 1591

The section is, of course, finally determined by the permissible heating and voltage-drop. For field-magnet windings see the rules in Chapter III., pp. 49 to 56.

(e) *Number of Armature Conductors*.—Under the standard conditions of flux-densities and gap-lengths adopted above, the number of ampere-conductors per inch of periphery (at full-load), should come out at about 600. Or, writing  $Z$  as the total number of armature-conductors,  $C_a$  as the total armature-current at full-load, and  $p$  as the number of poles, the current in any one conductor will (for parallel-wound armatures) be  $= C_a \div p$ . Hence the total number of ampere-conductors all round the armature (sometimes called the “circumflux”) will be  $Z \times C_a \div p$ ; and this, by the above rule, ought not to exceed 600 times the number of inches all round, or  $600\pi d$  where  $d$  is the diameter in inches. This gives, as a formula for calculating the trial-value of  $Z$ ,

$$Z = \frac{1885 \times p \times d}{C_a} . . . . [\alpha]$$

For armatures with series or series-parallel windings, where

there are  $c$  circuits (see pp. 85 and 97) through the armature (instead of  $p$  circuits) the rule becomes

$$Z = \frac{1885 \times c \times d}{C_a} \quad . \quad . \quad . \quad [\beta]$$

But these rules give values that are often wide of the mark. Another, and for some purposes better rule is this:—First obtain a trial value for the magnetic flux  $N$ , and then calculate  $Z$  from the electromotive-force and speed. Using  $n$  for the revolutions *per second*, and  $E$  as the volts at no-load, the formula for parallel-wound armatures is

$$Z = \frac{E \times 10^8}{n \times N} \quad . \quad . \quad . \quad [\gamma]$$

In every case the trial-number when obtained will need to be adjusted so as to give a proper multiple for winding.

*Example.*—Required the proper number of armature conductors for a dynamo M P—8—200 kw. — 375 r.p.m. — 125 v. — 16000 A. Taking the diameter of armature as 48 inches, and the trial value for the flux  $N = 4 \times 10^8$ ; by formula  $[\alpha]$ , the value of  $Z$  comes out 451; by  $[\gamma]$  it comes out 500. The actual value of  $Z$  in the machine (as built at Schenectady) was 480.

(f) *Number of Commutator Segments.*—The value of the average volts per bar of the commutator furnishes to a certain extent a sparking criterion of a machine, as they measure the inductive action of each individual section of the winding. If the suitable number of volts per segment is known, one at once obtains an estimate of the number of segments in the commutator by dividing the prescribed voltage of the machine by the suitable number of volts per segment, and then (for parallel-wound machines) multiplying by the number of poles. Or, in the case of armatures with series or series-parallel windings, multiplying by the number of circuits.

<sup>1</sup> Arnold (*Die Ankerwickelungen*, 3rd ed., 1899, p. 278) gives a formula as follows:—That the number of commutator segments must *not be less than* 0.037 to 0.04 times the product of  $Z$  into the square-root of the current in any one circuit of the armature. For example, in a 4-pole machine with four circuits, each carrying 100 amperes, and having 336 armature conductors, Arnold's rule would fix

For machines having flux-densities as assumed above, the following values are found.

For Machines working at	Average Volts per Segment.	Average Segments per Pole.
500 to 550 volts . . . .	5½ to 15	35 to 100
200 to 220 volts . . . .	4 to 10	20 to 50
100 to 110 volts . . . .	3	25 to 35

(g) *Size of Armature. Steinmetz coefficient.*—The question next arises, given the specification of a machine to be built on the above lines, how is the designer to begin with the calculations? Obviously he must get some idea how large the armature must be. Previous experience of the same type and size of machine will of course be sufficient to go upon, but failing this, use must be made of an empirical rule connecting the output of the machine with the over-all dimensions of the armature core. The simplest of such empirical rules is that originated by Mr. Steinmetz, that the product of the diameter of the iron core-body into its length is equal to the kilowatts of output of the machine multiplied by a certain coefficient; or in symbols

$$\frac{d \times l}{kzv} = \sigma.$$

Where  $\sigma$ , the Steinmetz coefficient, will have a value, if  $d$  and  $l$  are both in inches, not differing much<sup>1</sup> from 3. In old

the number of commutator segments as not less than  $0.037 \times 336 \times \sqrt{100} = 123$ . The machine actually had 168, two conductors making one loop as the element of the winding. Had the elements been of two loops each the number of segments would have been 84, which is too small. The machine would have sparked in all probability. Nevertheless it is certain that good machines have been constructed for which the constant was lower than 0.037, even as low as 0.025.

<sup>1</sup> If  $d$  and  $l$  are given in millimetres, the values of  $\sigma$  will range at about 2000, going down in large modern machines to 1250, or going up in small and slow-speed machines to 3500 or 4000.

There is a rational basis for this Steinmetz coefficient, for if it is assumed that there is a best average peripheral speed for the conductors moving in a field of

machines and machines of relatively small output, or of slow speed, the value of  $\sigma$  may go up to 5 or 6; for large and well-designed machines it may fall below 2. Of the various machines mentioned in this book the lowest value of  $\sigma$  is 1.44, being that of the Hobart design of 1600 kw., p. 229, while the highest is 13.4, being that of the very slow speed exciter of Kolben & Co., p. 217.

best average density, and that there is a fixed limit of temperature rise and a fixed ratio for the armature losses to the normal output, then the output ought to bear a constant ratio to the *working* surface of the armature—therefore proportional to  $d \times l$ .

Let  $v$  be the peripheral speed in inches per second,  $B$  the average flux-density (in lines per square inch) in the air-gap,  $\psi$  the ratio of pole span to pole pitch,  $W$  the full-load output in kilowatts,  $q$  the number of ampere-conductors per inch periphery, then the total polar area surrounding the armature is  $\pi \times d \times l \times \psi$  square inches. Now all the work done by the machine takes place under the poles; and we may write

Work done per second = peripheral force  $\times$  peripheral velocity,

which may be written

Output = force per unit surface  $\times$  total active surface  $\times$  peripheral velocity,

or

$$= B \times q \times \psi \times \pi \times d \times l \times v \text{ (ergs per second).}$$

$$W = B \times q \times \psi \times \pi \times d \times l \times v + 10^{11} \text{ (kilowatts).}$$

Now assigning to  $B$ ,  $q$ ,  $\psi$ , and  $v$  the respective average values 50,000, 600, 0.7, and 500, values which are found in good non-sparking machines, this becomes

$$\begin{aligned} W &= 0.33 \times d \times l, \\ 3.03 &= d \times l + W, \end{aligned}$$

whence

thus arriving rationally at the Steinmetz formula. Moreover, as the value of the constant was fixed by non-sparking conditions, it is clear that the limit of the output of the machine depends on heating alone;  $d \times l$  being a measure of the cooling surface. Thus under the assumption (which is found to be true in practice) that the limit to the output of machines of this type is put by heating, not by sparking, it follows that the value of the constant depends almost entirely on the *peripheral speed*. That is part of the reason for the differences observed in the examples given above, and furnishes a strong argument in favour of *high peripheral speeds*, and therefore of armatures tending toward the fly-wheel type.

Kapp has given a rule, which in British units ( $d$  and  $l$  in inches, and peripheral speed  $v$  in feet per minute), comes to this:—

$$d \times l = W \times \frac{c}{v};$$

where  $W$  is the full-load output in kilowatts, and  $c$  a coefficient which varies between the values of 35,000 for small ring-wound machines and slow-speed machines down to 7000 for large well-ventilated drum machines.

Examples.			Kilowatts.	Scrametr Coefficient.
Multipolar generator.	Engl. El. Mfg. Co., p. 220 .		1100	1·96
"	" Hobart's design, p. 229 .		1600	1·44
"	" " " " .		400	3·7
"	" Siemens & Halske, p. 232 .		1000	2·16
"	" Brown, Boveri & Co., p. 113 .		430	2·25
"	" " " " p. 203 .		194	2·47
"	" Kolben & Co., p. 216 .		250	4·35
"	" Walker Co., p. 173 .		440	3·6
"	" Gen. Elect. Co., p. 209 .		550	3·57
Bipolar	" Johnson & Phillips (1337) .		21	8·4

Having thus obtained a trial-value for the product of diameter and length of the armature core, it remains to separate it into these two factors. One method of doing this is to take the highest permissible surface speed; divide it by the number of revolutions per minute and by  $\pi$ , thus getting the largest permissible diameter as one of the desired factors. Another guide, assuming the number of poles to be fixed, is to assume (as is a fair rule for cast-steel pole-cores of circular section) that the length of the armature-core will be equal to half the pole-pitch at the armature surface; in which case the ratio  $d/l = 2 p/\pi$ ; whence  $d^2 = 2 kw \times p \times \sigma \div \pi$ .

Another rule connecting output and size is

$$kw = 0.064 \times d^2 l \times \text{revs. per min.};$$

where the coefficient 0.064 is a sort of mean, and will be greater for machines of greater specific output, therefore larger in the case of large modern machines than for small or old types. If the length  $l$  is assumed to be known we may deduce.

$$d = 7.9 \sqrt{\frac{kw}{\text{revs. per min.} \times l}}$$

(h) *Assignment of Losses of Energy.*—Losses in energy due to ohmic heating of the copper, to hysteresial and eddy-

current heating in the iron, and to friction are inevitable. They are discussed in the preceding chapter. Such losses must be kept down, because they lower the efficiency, and because an undue rise of temperature in any part is not permissible. Experience has shown that if a machine is to be so designed as not to overheat in any part, and to make the total loss of the minimum value compatible with economy of material, its various losses must be rightly apportioned out. The following may be taken as the apportionment of the losses in machines of different sizes :—

Output in Kilowatts.	Efficiency per cent.	Percentage Losses.				
		Armature.		Magnets.	Commutator Friction and Windage.	Total Losses per cent.
		Copper Loss.	Iron Losses.	Copper Loss.		
5 to 40	90	3·8	3·2	2·5	0·5	10
10 " 60	91	3·5	3·0	2·1	0·4	9
40 " 100	92	3·2	2·8	1·6	0·4	8
75 " 300	93	2·8	2·3	1·55	0·3	7
200 " 500	94	2·4	1·8	1·5	0·3	6
400 " 1000	95	1·9	1·5	1·35	0·25	5

Such a table would, however, be misleading unless it is borne in mind that the values may vary considerably even in machines of the same size for different speeds and under different conditions of working. For example, a 93 per cent. efficiency is in general too high for a 75-kilowatt machine, unless it is of very large size for its output. Such tables may however be drawn up with some accuracy for a standard series of machines of some one type, such as a series of slow-speed tramway generators, or a series of high-speed lighting machines. The following is a table of average values in a series of standard generators built by Messrs. Kolben & Co. (see next page).

Parshall gives the following apportionment for a 550-kilowatt tramway generator :—Armature copper 2·25; armature iron 2·25; magnets 0·75; commutator, etc., 0·75; total 6 per

cent. Rothert gives for similar machines:—Armature copper 2·7; armature iron 1·8; magnets 1·5; commutator 0·3; total 6·3 per cent.

Output in Kilowatts.	Speed.	Full-Load Efficiency per cent.	Full-Load Losses			
			Excitation Loss.	Commutator, Friction and Ventilation Loss.	Copper Losses.	Iron Losses.
50	550	92·6	800	1000	1,200	1,000
100	450	93·0	1500	1900	2,200	1,900
200	350	93·4	2800	3600	4,200	3,600
400	300	94·0	5000	6000	7,900	6,800
500	100	94·4	5900	6400	9,500	8,000
750	100	95·0	8000	7100	13,500	11,000

N.B.—The first four of these machines are high-speed lighting machines, suitable for coupling direct to a high-speed engine, and the loss due to the outer bearing is included in friction losses. The last two are slow-speed traction generators; and for these the efficiency figure does not include any loss at the bearings.

(i) *Centrifugal Forces*.—If a mass is whirling with a radius of  $R$  inches, at  $V$  revolutions per minute around an axis, the centrifugal force is  $0·0009138 RV^2$  *poundals* per pound of peripheral matter, or  $0·0000284 RV^2$  *pounds* per pound of peripheral matter. This rule can be used to estimate the centrifugal forces on armature conductors.

*Example*.—Suppose an armature conductor weighing 0·39 lb. to be revolving at 150 revolutions per minute; the radius of the armature being 31 inches. The centrifugal force on it will be

$$0·39 \times 0·0000284 \times 31 \times 150 \times 150 = 7·72 \text{ lbs.}$$

(j) *Calculation of Binding Wires*.—In the case of smooth cores the conductors must be secured in their places by a number of external bands, known as *binding wires*. In the case of toothed core-disks the conductors may be held in by *wedges* of hornbeam or of hard white fibre driven in under the tops of the teeth; or in the case of straight teeth binding wires may

be used instead of wedges. Binding wires must be strong enough to resist the centrifugal forces, and yet at the same time must occupy very little radial depth that they may not interfere with the clearance between the armature and the pole-faces. The almost invariable practice is to employ a tinned wire, of hard-drawn brass, phosphor bronze, or steel, which, after winding, can be sweated together with solder into a continuous band. Mr. Wall, of Sheffield, manufactures a special "plated steel" wire for binding, in sizes of 18, 22, 28, 36, 48 and 56 mils diameter respectively. Phosphor bronze will withstand a tensile stress of from 65,000 to 120,000 lb. per square inch. Steel varies from 125,000 to 230,000 lb. per square inch.

To estimate the proper size and number of binding wires required we may remember that on a pound of material at a radius of  $R$  inches, revolving at a given speed the centrifugal force will be that given by the formula on p. 144. Or if  $d$  be the diameter in inches, and  $n$  the revolutions per second, the centrifugal force per pound of matter will be  $= 0.012 d n^2$  pounds' weight.

Suppose we know the mass  $w_1$  (in pounds) of one conductor, multiplying this by the total number of conductors  $Z$ , we get the total mass of armature conductors, and dividing by  $\pi$  we find the mass that will be effectively projected in any one direction. Putting this into the formula, and dividing by 2, we find the total tensile force to be borne by the binding wires at one side; and dividing again by the maximum tensile stress which the material can stand, we obtain the net theoretical total cross section of the whole of the binding wires. Taking a factor of safety of 10, and a value of 100,000 lbs. per square inch as the tensile stress for steel or for phosphor bronze we get total necessary section of binding wires in square inches

$$= \frac{w_1 \times Z \times 0.012 \times d'' \times n^2 \times 10}{2 \times \pi \times 100,000};$$

$$= \frac{1.623 \times w_1 \times Z \times d'' \times n^2}{1,000,000}.$$

From this total necessary section, and the appropriate wire-

gauge, the number of wires is then calculated, and they are then arranged in suitable belts.

*Example.*— $w_1 = 0.39$  lb.;  $Z = 1536$ ;  $d = 62$ " ;  $n = 2.5$  revs. per sec.; total necessary section works out to  $0.386$  square inch. Referring to wire-gauge tables we find a No. 17 S.W.G. of diameter 56 mils, has a cross-section of  $0.00246$  square inch. Dividing  $0.386$  by  $0.00246$  we find that 156 wires are needed. These may be arranged as follows: 5 belts of 16 wires each over the core body and 4 belts of 19 wires each over the extended ends of the winding, *i.e.*, 2 belts of 19 wires each over each end.

Under each belt of binding wires a band of insulation is laid. This usually consists of two layers, first a thin strip of thin vulcanized fibre or of hard red varnished paper, slightly wider than the belt of wires, and then a strip of mica (in short pieces) of about equal width. Some makers lay a small strap of thin brass under each belt of binding wires, having tags which can be turned over, and soldered down, to secure the two ends of the binding wire from flying out.

#### ORDER OF PROCEDURE IN DESIGN.

The specified conditions to be fulfilled are that the dynamo, running at a prescribed speed (fixed by the choice of engine), shall give out its current at a prescribed voltage, and that when running at normal full-load of a prescribed number of amperes it shall have a prescribed efficiency.<sup>1</sup>

The method of getting out a preliminary design to a given specification is, therefore, as follows:—

The example which is here given is continued for the remainder of this section.

*Example.*—To design a tramway generator to give, at 150 revolutions per minute, 600 amperes at 500 volts, the efficiency being 93 per cent.

<sup>1</sup> Other details may be prescribed, for example, the limit to which temperature is allowed to rise, the amount to which the machine shall be compounded or overcompounded, the efficiency at  $\frac{1}{2}$  or  $\frac{3}{4}$  load, the permissible amount of temporary overload, and the like.

(1) Find the full-load kilowatts by multiplying together the volts and the full-load amperes, and dividing by 1000.

*Example.*—As above, 300 kilowatts.

(2) Assume a suitable value for the Steinmetz coefficient (remembering that its value is reduced the higher the permissible peripheral speed), and proceed by multiplying the required number of kilowatts by this coefficient to find the product of  $d \times l$ .

*Example.*—Taking  $\sigma = 3.13$ , we find  $300 \times 3.13 = 939$ . That is to say we know that  $d$  and  $l$  must be such that  $d \times l$  (in inches) = 939.

(3) Fix a trial-value for the number of poles (see p. 137 above).

*Example.*—As the full load is 600 amperes, a 6-pole design would do; but to be quite sure of avoiding trouble as to sparking let us take 8 poles, so that with a parallel-wound armature there will be 8 circuits and only 75 amperes in each circuit, or 150 amperes to collect at any one row of brushes.

(4) Fix the value of  $d$  and  $l$  separately, putting down trial-values by experience, and test them by observing what surface-speeds they correspond to, and whether any of them agrees with the rules laid down above (p. 142). In particular see whether the proportions chosen are suitable for the number of poles provisionally selected.

*Example.*—We may at once put down a number of trial values of  $d$  and  $l$  as follows:

$l$	$d$	$d \times l$	Peripheral Speed
12	78	936	3062
14	67	938	2631
15	62	930	2434
16	58	928	2277
18	52	936	2041

Calculating the peripheral speeds that correspond to the different diameters at 150 revolutions per minute we see that the diameter which gives us the surface speed nearest to the moderate value of 2400 feet per minute is 62 inches. The periphery of this armature will be  $62 \times \pi$

= 194.75 inches. Dividing by 8 we get the pole-pitch at the armature face as 24.34, and as the pole-face will cover about 80 per cent. of this, the pole-arc will be about 19 inches long; making the actual pole-face about 19 by 15 inches, which is a suitable shape.<sup>1</sup> We may take it then that the values of  $d$  and  $l$  will be 62" and 15".

(5) Fix the value of  $Z$ . The preferable mode of doing this is, now that the size of pole-face is approximately known, to assume a provisional value for the flux from the pole, and calculate  $Z$  from the voltage by the fundamental formula

$$E = \pi ZN \div 10^8,$$

or from the variety of it given on p. 139 above. The provisional value of  $N$  is found by assuming a suitable flux-density, and multiplying this into the area of pole-face provisionally found.

*Example.*—The pole-face being  $19 \times 15 = 285$  square inches, if the flux-density at the pole-face be taken at 45,000 lines per square inch (a low estimate allowing for increase at full load), then  $N$  the flux from one pole will be about 13,000,000 lines. Now at 150 revolutions per minute the value of  $n$  will be  $150 \div 60 = 2.5$  revolutions per second. Hence if  $E$  is 500 volts we provisionally find  $Z$  as

$$500 \times 10^8 \div (2.5 \times 13,000,000) = 1538.$$

But, for parallel windings (lap-windings), it is preferable that  $Z$  should be an even multiple of the number of poles, in this case 8. Now 1538 is not a multiple of 8, but 1536 is an even multiple; therefore, we will take  $Z$  as 1536. But before finally deciding on this value we must test it by the other requirements. If we apply the formula [a] on p. 138, we find  $Z = 1885 \times 8 \times 62 \div 75 = 1579$  as the highest number permissible if there are not to be more than 600 ampere-conductors per inch periphery. So  $Z = 1536$  is satisfactory.

At this point we ought to pause and test the consequences of our procedure so far. Let us test the number of poles by the rules given on p. 137.

<sup>1</sup> If it is required that the poles should be of cast steel and circular in section, there might be some advantage in having a more elongated shape for the pole-face, for example,  $21\frac{1}{4}$  inches by 14 inches, which would be the size had the 67-inch core-disk been selected.

*Example.*—The number  $Z$  is 1536, and each conductor carries 75 amperes; multiplying these together, and dividing by 14,000, we get 8.3, justifying our selection of 8 poles.

Further, as the speed is  $n = 2\frac{1}{2}$  revolutions per second and the number of pairs of poles 4, the frequency of magnetization in the armature is 10 cycles per second, which ensures that iron-losses in the armature can be kept low.

(6) Fix the number of commutator segments. Lap-wound armatures may have one segment for each loop of two conductors. Modern practice is against having more loops than one<sup>1</sup> per segment, so as to keep down the average voltage per segment. In all cases it is well to keep the number of segments high.

*Example.*— $Z = 1536$ , or 192 conductors per pole. That makes 96 loops per pole, with an average voltage of  $500 \div 96 = 5.2$  volts per loop. As it is undesirable that the volts per segment should be unnecessarily increased, we will decide to have 768 segments in total, or 96 per pole. Arnold's rule, p. 139, prescribes as the minimum number  $0.037 \times Z \times \sqrt{C_1}$  where  $C_1$  is the current in one conductor. In this case we have  $0.037 \times 1536 \times \sqrt{75} = 492$ . Now 768 is above this number, whereas if we had tried having two loops per segment and only 384 segments we should have gone below the permissible limit.

It being then decided that the commutator shall have 768 segments, since each segment cannot be much less than 0.2 inches broad, the commutator will have to be nearly 150 inches in periphery, or say 45 inches in diameter.

(7) Next settle upon the style of armature-winding. Modern practice tends toward preserving the utmost simplicity, that is to say, it favours the lap-wound drum executed as a barrel-winding so as to have ample cooling surface, the conductors being in two layers, and with two, four or six conductors in each slot. It is true that some designers still prefer to use series-parallel windings, as they have the advantage of enabling fewer armature conductors to be used for the same voltage, and

<sup>1</sup>For a case to the contrary, see Brown, Boveri and Co.'s 8-pole machine, p. 204. In motors under 50 H.P. it is usual to have more than one turn per section.

these conductors are thicker; and (as shown on p. 109) they give rise, in case of irregularity in the strength of the poles, to less internal heating from unequal currents in the different circuits. Some examples of designs with series-parallel windings will be found in the following machines :—

Kolben and Co.'s 10-pole, 250 kilowatt machine, p. 216.

Oerlikon Co.'s 12-pole, 350 kilowatt machine, p. 188.

Brown, Boveri and Co.'s High Voltage 4-pole, p. 205.

At one time designers favoured the custom of adapting one and the same armature core so that it could be wound with the same number of conductors for 125, 250, and 500 volts provided the magnet had 4 or 8 poles: for if the 250 volts were simply a parallel (lap) winding with as many circuits as poles, the 125-volt armature would be also a duplex parallel (lap) winding (p. 83), with twice as many circuits as poles, and the 500-volt armature a series-parallel wave-winding with only half as many circuits as poles.

The object of fixing the type of construction is that an estimate may be made of the available cooling-surface. For barrel-winding the length to which the oblique end parts of the winding extend out will be about equal to half the pole-pitch on each side of the core-body.

*Example.*—The pole-pitch is 24·34 inches. Adding half this, or say 12½ inches, to each face of the armature core-body, which is already 15 inches long, makes the over-all length of the armature (without the commutator) 40 inches.

(8) Next decide upon the apportionment of the various losses. This might have been done at an earlier stage. The figures given on p. 143 will assist in apportioning the various losses. The exposed surface of the armature should have not less than 18 to 20 square inches for each kilowatt of output (see p. 69), otherwise the temperature cannot be kept within permissible limits with these percentages of loss. If on reckoning out the losses it is found that the armature surface is insufficient, the armature must be re-designed of larger size.

*Example.*—Assuming the copper-loss in the armature to be 2.5 and the iron-loss to be 2.0 per cent., or in total  $4\frac{1}{2}$  per cent. of the output, the total watts wasted in the armature will be  $4\frac{1}{2}$  per cent. of 300,000 watts, or 13,500 watts. The periphery of armature being 194.75 inches and the over-all length 40 inches, the total area of the cylindrical surface is 7790 square inches. Each square inch must therefore radiate away 1.735 watts. As the surface speed is 2434 feet per minute, a reference to the curves of Fig. 22, p. 70, will show a probable rise of temperature of  $45^{\circ}$  C. On this estimate it would be preferable to reduce the copper-loss by using a slightly thicker conductor.

According to the rule given above, the surface of the armature ought to be from 18 or 20 times 300, *i.e.* 5400, or 6000 square inches. As it has 7790 there should be ample surface.

(9) Next we may settle upon the number and dimensions of the slots. The former depends upon the type of the armature winding used and the number of commutator-segments. It is almost universal now-a-days for all large machines to wind with copper strip, two layers (or sometimes four layers) deep. But whether the slot is made wide enough to carry two, four, or six conductors depends on the conditions. Putting four or six conductors in one slot simplifies the construction and saves labour. It also saves some space, and should be adopted if there is fear of not having sufficient tooth-section for magnetic purposes. In 500-volt generators the depth of the slot varies from 1 to 2 inches or so. Assuming a proper trial value for the current density (see p. 138) in the conductors, their proper section can be at once provisionally assigned. And, if the grouping has been chosen, the necessary area of each slot can be reckoned out by aid of a space-factor (p. 45). It must then be considered whether this leaves an adequate section for the tooth. Since the average flux-density in the air-gap is, say, 50,000 lines per square inch, and the appropriate flux-density in the teeth is 130,000 lines per square inch, one would expect the teeth to take up only five-thirteenths of the periphery. But it must be remembered that the iron of the teeth is not continuous, there being insulation, and often air-ducts, between the laminations. In the case of slots with parallel straight sides it is usual to find the width of the tops of the teeth about as great as, or

slightly narrower than the width of the slots; and as the teeth slope slightly down to their roots their mean width will be less than that of the slot, and is indeed generally about three-quarters of that width. The number and arrangement of the conductors should now be readjusted to suit winding conditions.

*Example.*—As each conductor has to carry 75 amperes, the appropriate section at 2000 amperes per square inch will be 37,500 square mils ( $= 0.0375$  square inch). If we decide to place these 6 in a slot the total copper section per slot will be 0.225 square inch. Taking the space-factor as 0.4, we have the area of slot as  $0.225 \div 0.4 = 0.562$  square inch at least; and as there will be 256 slots and 256 teeth in a total perimeter of 194.75 inches, each slot cannot well be more than 0.38 inch wide, each must be *at least* 1.5 inches deep.

(10) The internal diameter of the core may now be fixed, by ascertaining the requisite radial depth of the core to give an adequate cross-section of iron below the teeth. As a trial-value one may take *either* the face-diameter of the armature divided by the number of poles, *or* a length equal to half the pole-arc. But the final adjustment of this radial depth depends purely upon the permissible iron-loss, as this governs the flux-density that can be used.

*Example.*— $d = 62$  inches, and as there are eight poles the trial value of the radial depth is  $7\frac{1}{2}$  inches; or, the pole arc being 19 inches, the half of this is  $9\frac{1}{2}$  inches. We may provisionally take a mean value such as  $8\frac{1}{2}$  inches, which, if the slots are estimated at  $1\frac{1}{2}$  inches deep, brings the internal diameter to 42 inches. Now the flux through the armature-core is  $\frac{1}{2}$  N or 6,500,000 lines. The nett length of iron from front to back being about 11.7 inches, the nett sectional area will be about 100 square inches, giving a flux-density of about 65,000, which is satisfactory (see p. 136), and will ensure that the iron losses are not too great.

(11) Next, settle the dimensions of the air-gap by the principles laid down on p. 39.

*Example.*—As the slots are 0.3805 inches wide at the top, the length across the gap ought not to be less than 0.5 inch. This is sufficient

as a clearance on an armature 62 inches in diameter, but unless there is some reason to the contrary, it would be with advantage larger: so we will adopt 0.65 inches.

(12) Fix the approximate dimensions of the magnet-pole cores. These must have sufficient cross-section to carry the full-load flux, including that which forms by leakage the stray field; and they must be long enough to receive the exciting bobbin. The flux will be  $\nu \times N_a$ ; where  $\nu$  is the coefficient of dispersion,  $N_a$  being taken at its full-load value. A good trial-value for the length of the pole-core, if cylindrical, is to make it equal to the diameter of the section, though this may generally be reduced after the magnetic circuit calculations have been made to ascertain what provision must be made for excitation. Another rough way of obtaining a trial value for the length of the pole is to take 20 times the length of the air-gap, if the machine is to be shunt-wound, or 40 times the length if it is to be over-compounded. The section necessary is fixed by the permissible flux-density (see p. 136).

*Example.*—The no-load armature flux per pole being 13,000,000 the full-load flux will need to be (for a shunt machine or compound-wound, but not over-compounded machine) say 13,500,000. Taking the coefficient of dispersion as  $\nu = 1.21$  at full load, it follows that  $N_m$  must be 16,400,000. Then taking 105,000 lines per square inch as a suitable value for the flux-density, there will be required 157 square inches. Hence the pole-core, if circular, must be 14 inches in diameter; or, if square, about  $12\frac{1}{2}$  inches each way. Taking the other rule, if the air-gap is 0.65 inch, multiplying this by 20 gives 13 inches as a suitable trial-value for the length. We may therefore take 13 inches provisionally as its length.

(13) The necessary cross-section and size of the yoke may then be fixed: the section being as before fixed by the appropriate flux-density.

*Example.*—The yoke has to carry  $\frac{1}{2}N_m$  lines, in this case 8,200,000, at full-load. Suppose it to be of cast-iron with an appropriate density not exceeding 40,000 lines per square inch. Then about 205 or 210 square inches will be needed. Being of cast-iron, a broad semi-oval

section, flat in the inner face, will be appropriate, and if a breadth of 30 inches with a thickness of 9 inches at the middle be adopted, the over-all diameter of the magnet frame will be about 108 inches.

(14) All is now provisionally ready for the commencement of the real calculation of the machine. A drawing should be sketched out to scale, using the trial-values adopted so far. This drawing will enable the designer to judge of the ultimate dimensions and appearance of the machine. From it a complete set of calculations must now be made (on the principles laid down in the preceding chapters) for (1) excitation, (2) heating, (3) sparking, and (4) efficiency, as is done in the case of the two machines discussed below. On examining the results of such calculations it is then easy to see in what manner it would be desirable to alter the design in order to fulfil more completely the specified conditions. Finally, as the outcome of such considerations, other designs ought then to be made, and worked through, differing in various ways from the first one, but fulfilling the terms of the specification. For example, if the sparking-criteria are only barely fulfilled, it might be worth while to recalculate after slightly increasing the diameter of the armature: or if they are amply fulfilled, the diameter might be slightly reduced. Or if the percentage of the heat-losses in any of the parts—say the teeth—comes out either higher or lower than the amount known by experience to be advisable, then the design might be modified so as to give either a higher or a lower flux-density, as the case may be, in that part. When a few such variants on the first design have been made it becomes a simple matter to pick out that design which appears to be the best all round, cost of materials and cost of manufacture being the most important final consideration.

Machines intended to be used as over-compounded generators must be designed a little more liberally than those designed for same speed and voltage as shunt machines, so as to allow for the increase of magnetic flux and additional excitation losses at full load; or, what comes to the same thing, if of equal dimensions, they must for the same speed be rated as of, say,

from 5 to 7 per cent. lower output; or, if rated at the same output, their speed must be increased from 5 to 7 per cent.

*Other Procedure in Design.*—It is, of course, possible to follow a different order of procedure in designing. Rothert, in an excellent paper in the *Elektrotechnische Zeitschrift* for 1901, gives the following:—Using for the estimating of the armature dimensions a constant which differs in different types of machine, but which, for a given diameter, determines the length of the core, he then chooses the number of poles in dependence chiefly on the prescribed speed. His rule for this is that the frequency (i.e. the product of number of pairs of poles into revs. per second) shall lie between 17 and 20 for 500-volt machines, or between 18·5 and 22 for those over-compounded to 550 volts. From this he selects the armature dimensions so that, taking the pole-span about 72 per cent. of the pole-pitch, the pole-face shall be approximately a square, about the middle of which is centred a cylindrical steel pole. He does not calculate up the efficiency until after the main dimensions have been settled, as he finds it always to come out right, in the case of large machines, if they are only approximately correctly designed in other respects. Much more important he regards the cooling question, which can, however, be controlled by providing due ventilation. The two main factors, however, which are of vital influence in selecting dimensions are the proper magnetic saturation of the teeth, and the economy of material attained by using high current-densities in the copper. As to the former, he uses 151,000 lines per square inch (apparent) at full load. As armature current-density, he takes 1700 to 1900 amperes per square inch. Allowing a temperature-rise of 35 deg. C., and surface speeds of 1700 to 2300 feet per minute, he finds this to correspond to a waste of about 1·61 to 2·13 watts per square inch of peripheral armature surface. For the stationary coils of field-magnets he allows a current-density of 900 to 1060 amperes per square inch; and with a permissible temperature rise of 35° C., a corresponding waste of 0·77 watts per square inch of cylindrical surface.

*Criteria of a good Design.*—A well-designed machine must not spark at any load up to an overload of 50 per cent. above

normal. It must not spark (see p. 159) at any load up to overload of 25 per cent., even though the brushes be fixed must not overheat (see Chapter VI.). And it must be neither too heavy nor too costly in manufacture.

A good criterion is *the ratio of the flux-density in the air-gap to the ampere-conductors per inch of periphery*. The former has usually values approximating to 50,000, while the latter varies usually from 500 to 600. This ratio is, therefore, of the order of magnitude of 80 to 100. It may be briefly called the *stiffness-ratio*. If higher, the machine is unnecessarily heavy; if lower, it may be prone to spark at high loads.

Another criterion of goodness of commutation is the value of the stiffness-ratio as compared with the volts per segment of the commutator. The latter varies (see p. 140) in machines of different voltages. In 100-volt machines the voltage per segment may be taken as about 3. In these, then, the stiffness-ratio (of 80 or 100) divided by 3 gives the *commutation-ratio* as 27 to 33. In 500-volt machines, taking voltage per bar as about 6, gives 13 to 16 as the commutation-ratio. Any lower value than these should be looked upon with suspicion.

Yet another criterion is to compare the number of ampere-turns of excitation needed at full-load to drive the flux through the gap and teeth, with the whole number of ampere-conductors (at full-load) that lie under one pole-face. This is a comparison in effect between the magneto-motive force that tends to resist distortion, with the ampere-turns tending to distort the field. A couple of examples from machines known to commute well at all loads will suffice:—

In Parshall's 550 kilowatt generator, p. 209, the number of ampere-turns spent on gap and teeth is 6600 per pole, while the distorting ampere-conductors under one pole amount to 14400, making the ratio of the former to the latter 0·45.

In the Scott and Mountain 150 kilowatt generator, p. 210, the ampere-turns for gap and teeth amount to 8350, while the distorting ampere-conductors are 13,000, making the ratio 0·64.

As to weights, machines with a low peripheral speed always weigh more than those of equal output with a high speed;

those with cast-iron yokes more than those with steel yokes. The armature weight (apart from the shaft) ought to be approximately proportional to the kilowatts if equal peripheral speeds are attained.

Hobart has considered<sup>1</sup> the problem of designing series of generators of standard patterns to cheapen manufacture. His designs favour a high surface speed, large commutator, and high current-density in the armature, from 2340 to 2520 amperes per square inch.

*Specific Utilization of Material.*—Mavor has introduced<sup>2</sup> the conception of the "active belt," meaning by this term the entire mass of the armature periphery down to the roots of the teeth, consisting of iron, copper, and insulation. It is in this active belt that the whole inductive generation takes place, and on this active belt that the mechanical forces are exerted. Mr. Mavor found the number of ergs per second per cubic centimetre at unit velocity in unit field to be about 5. But the work done per line in moving a current across a field is simply proportional to the current: so that Mr. Mavor's figure is a measure of the current-density in the gross section of the active belt.

We may extend still further this conception of a belt of active material, and may consider not only the mean number of amperes that traverse each square inch of it parallel to the shaft, but also the mean number of magnetic lines that traverse each square inch of it radially, and the speed with which it moves forward tangentially. Let us consider the number of watts generated per cubic inch of the active belt. If  $d$  be the diameter,  $l$  the length of the core-body, and  $s$  the depth of the slot (or length of the tooth), the total volume of the active belt will be  $\pi d l s$ . Hence:—

$$\text{Watts per cubic inch} = \frac{E C}{\pi d l s}$$

Now, writing for  $E$  the value  $n Z N p \div c 10^8$ ; and re-

<sup>1</sup> *Journal Institution Electrical Engineers*, xxxi. 170, 1901.

<sup>2</sup> *Ibid.*, xxxi. 218, 1901.

membering that  $n = v \div \pi d$ , where  $v$  is the peripheral velocity in inches per second, we have:—

$$\text{Watts per cubic inch} = \frac{Z C N p v}{c \pi^2 d^2 l s \cdot 10^8}.$$

This we may decompose into three factors, thus:—

$$\text{Watts per cubic inch} = \frac{Z C}{\pi c d s} \cdot \frac{N p}{\pi d l} \cdot \frac{v}{10^8}.$$

These three factors we may severally write:—

$$Z C \div \pi c d s = a = \text{gross current-density per square inch in active belt.}$$

$$N p \div \pi d l = \beta = \text{gross magnetic density per square inch in active belt.}$$

$$v \div 10^8 = \gamma = \text{a quantity proportional to the peripheral velocity.}$$

If, then, we take out these three factors,  $a$ ,  $\beta$ , and  $\gamma$  for any particular machine, we have at once a means of comparison between its design and that of other machines in respect of the specific utilization of materials. Some makers manage to crowd many amperes through the copper: in their machines  $a$  will be large. Other makers contrive to have a high average flux-density in the belt: in their machines  $\beta$  will be large. Others drive their machines with a high surface speed, and so increase the specific output of a given quantity of active material. Owing to the conditions that are necessitated by sparkless commutation  $a$  cannot be very high unless  $\beta$  is high also, though  $\beta$  may be high without  $a$  being so. And  $\gamma$  may be high or low, quite independently of  $a$  or  $\beta$ .

The Author has therefore made a detailed examination of more than fifty modern generators, including the machines mentioned in this book, to ascertain the values of these three factors of specific utilization. The values of  $a$  for machines of the type principally dealt with lie mostly between 300 and 460, a few being outside these limits. The values of  $\beta$  lie mostly between 30,000 and 45,000, the extreme values being 22,000 and 58,000. The values of  $\gamma$  lie mostly between 0.000004 and 0.000009;

but in a few cases exceed the latter figure. The watts per cubic inch of active belt run from about 45 to 120; but in one case go down to 15, and another case, Hobart's 1600 kw. generator, reach 162. Smooth-core machines are not included in these calculations, nor arc-lighting machines, nor magnetic machines, nor any small designs. See the Table on p. 234.

*Sparking Criteria.*—A rule much used by designers is that the flux-density under the backward pole-horn at full load shall not be reduced below about 13,000 lines per square inch. Or if  $X_g$  denote the ampere-turns per pair of poles required for the double air-gap,  $X_c$  the number of ampere-conductors under one pole, and  $B_g$  the average flux-density in the gap at full load, then

$$B_g \times (X_g - X_c) \div X_g \text{ shall not fall below } 13,000.$$

Mr. Kapp has suggested two other criteria, involving the use of arbitrary coefficients, which are here stated in British units.

Let  $B_g$  be the flux-density (lines per square inch) in the gap.

"  $X_c$  be the number of ampere conductors per inch of armature periphery,

"  $K$  be the total number of commutator segments,

"  $k_2$  be the number of commutator segments short-circuited together by any one brush,

"  $Y_1$  be an empirical constant,

"  $Y_2$  be a second empirical constant,

"  $g$  be the length across one air-gap (iron to iron), in inches,

"  $d$  be the diameter of the armature, in inches.

Then the *first* criterion is that

$$Y_1 = B_g \times k_2 \div X_c;$$

where for good results, in

slotted drum armatures,  $Y_1$  should not come less than 38

"	ring	"	"	"	"	60
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The *second* criterion is that

$$Y_2 = K g \div d (1 + k_2);$$

where for good results

with metal brushes,  $Y_2$  should not fall below the value 1.2

"	carbon	"	$Y_2$	"	"	"	0.6
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## CHAPTER VIII.

## EXAMPLES OF DYNAMO DESIGN.

WE now proceed to analyse the designs of two machines of different types, as examples of the foregoing principles and methods.

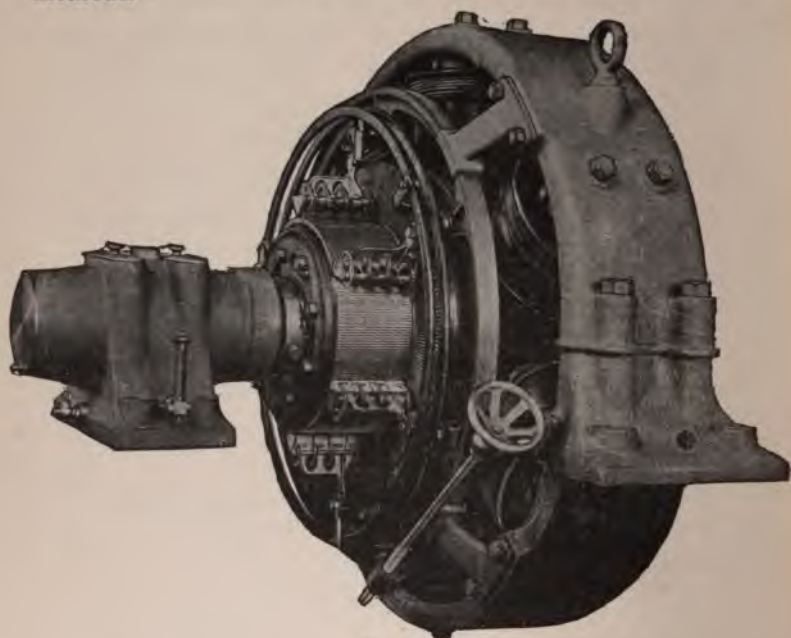


FIG. 55.

*Example I.*—SHUNT-WOUND MULTIPOLAR MACHINE  
WITH SLOTTED DRUM ARMATURE.

Built by Messrs. Ernest Scott and Mountain.

M.P.—6—150—450—250 volts—600 amps.  
(Shown in Figs. 55 & 70, and Plate II. For description,  
see page 198.)

The leading dimensions and particulars as obtained from the drawings are given in the schedule form below.

GENERAL SPECIFICATION.

Full load (kilowatts) . . . . .	150
“ (terminal volts) . . . . .	250
“ (amperes) . . . . .	600
Revolutions per minute . . . . .	450
Peripheral speed (feet per minute) . . . . .	2835
Number of poles . . . . .	6
Nature of load . . . . .	Lighting

DIMENSIONS.

Armature:—

Core disks, external diameter (inches) . . . . .	33
“ internal “ “ . . . . .	18
Number of slots . . . . .	124
Depth of slot (inch) . . . . .	1·625
Width “ “ . . . . .	0·4
Pitch of slot at armature face (inch) . . . . .	0·840
“ “ average (inch) . . . . .	0·796
Depth of iron in core, under teeth (inches) . . . . .	5·875
Gross length of core (inches) . . . . .	11
Iron “ “ “ . . . . .	9
Diameter of finished armature (inches) . . . . .	33
Number of conductors . . . . .	496
Arrangement . . . . .	4 in slot
Style of winding . . . . .	parallel
Dimensions of each conductor, bare (inches) . . . . .	0·7 × 0·11
“ “ “ insulated (inches) . . . . .	0·73 × 0·14
Section of each conductor (square inch) . . . . .	0·077
Mean length, one armature turn (inches) . . . . .	66

Field-Magnets:—

Diameter of bore (inches) . . . . .	33·625
Polar angle (degrees) . . . . .	43
Turns per pair of poles . . . . .	3602
Mean length of one turn (inches) . . . . .	43
Diameter of wire, bare (inch) . . . . .	0·09
Section of wire (square inch) . . . . .	0·0050
Shunt current (amperes) . . . . .	4·10

Commutator:—

Diameter (square inches) . . . . .	21
Number of segments . . . . .	248
Active length (inches) . . . . .	7·5

An inspection of the drawings shows that the magnet cores of steel are of circular section, bolted on to the yoke, the pole pieces being in one piece with the magnet cores.

The field-frame is cast in two pieces and bolted together. All the field-bobbins are connected in series. The armature slots are straight, and of the dimensions given above. These are two ventilating apertures, each  $\frac{3}{8}$  inch wide, and the core disks are insulated with varnish, deducting altogether 18 per cent. from the gross section.

The armature winding has six parallel circuits, and six sets of brushes at  $60^\circ$  apart.

We will first construct the saturation curve of the machine.

We have:—

$$E = n \times Z \times N_a \div 10^8,$$

or

$$E = \frac{450}{60} \times 496 \times N_a \div 10^8;$$

$$E = 0.00000372 N_a.$$

The dispersion coefficient of this machine is  $\nu = 1.17$ .

Hence we have:—

E	$N_a$	$N_m$
300	8,100,000	9,480,000
280	7,530,000	8,800,000
260	7,000,000	8,200,000
230	6,180,000	7,230,000
200	5,400,000	6,320,000

From the drawings we obtain:—

Length of mean magnetic path in magnet yoke (inches)	26
“ “ two magnet cores (inches)	28
“ “ armature core “	15
“ “ two teeth “	3.250
“ “ two air-gaps (inch)	0.625

And for the magnetic areas:—

For the yoke (square inches)	. . . . . = 44
“ magnet cores (square inches)	. . . . . = 78.5
“ armature body “	. . . . . = 53.0

The polar angle being  $43^\circ$ , we have for the number of teeth under one pole

$$\frac{124 \times 43}{360} = 14.7.$$



$$E = 260.$$

$$N_a = 7,000,000.$$

$$N_m = 8,200,000.$$

Part of Machine.	Material.	Magnetic Length.	Magnetic Section.	Flux Density.	Value of $\delta$ from Curve.	Ampere-Turns.
Yoke	cast steel	26 in.	2 sq. in. $\times 44$	93,200	34	884
Two magnet cores	cast steel	28	78.5	104,300	60	1,680
Two air-gaps	air	0.625	102	68,600	(per $\frac{215}{100}$ inch)	13,430
Two teeth	{ iron stampings }	3.250	64	109,000	107	348
Armature core	{ iron stampings }	15	2 $\times$ 53	66,000	4	60
Total ampere-turns per pair of poles 16,402						

In the same way we calculate other points of the curve obtaining:—

When

$$E = 200, \text{ necessary ampere-turns} = 11,251$$

$$E = 280 \quad \quad \quad \text{“} \quad \quad \quad \text{“} \quad \quad \quad = 20,298$$

$$E = 300 \quad \quad \quad \text{“} \quad \quad \quad \text{“} \quad \quad \quad = 25,915$$

By plotting the curve connecting these five points we obtain the working part of the saturation curve, as shown in Fig. 56. We have then for  $E = 250$  volts;

$$\text{Necessary ampere-turns at no-load} = X_1 = 15,300.$$

We will now proceed to find the necessary ampere-turns at full-load. These will be greater than those required at no-load by an amount depending upon:—

1. The value of the full-load lost volts.
2. Amount of armature demagnetization.
3. “ “ distortion.

Now the resistance of the armature including brush-leads and carbon brushes is 0.0081 ohm brush-to-brush at the working temperature.

The resistance of the series coils is 0.00083 ohm.

Hence the total resistance of the main current circuit in the machine is  $(0.0081 + 0.00083) = 0.00893$  ohm.

The full-load drop is therefore:—

$$e = 600 \times 0.00893 = 5.3 \text{ volts.}$$

Now the terminal voltage of the machine at full-load is 250.  
Hence the armature must generate at full-load  $250 + 5 \cdot 3$   
 $= 255 \cdot 3$  volts.

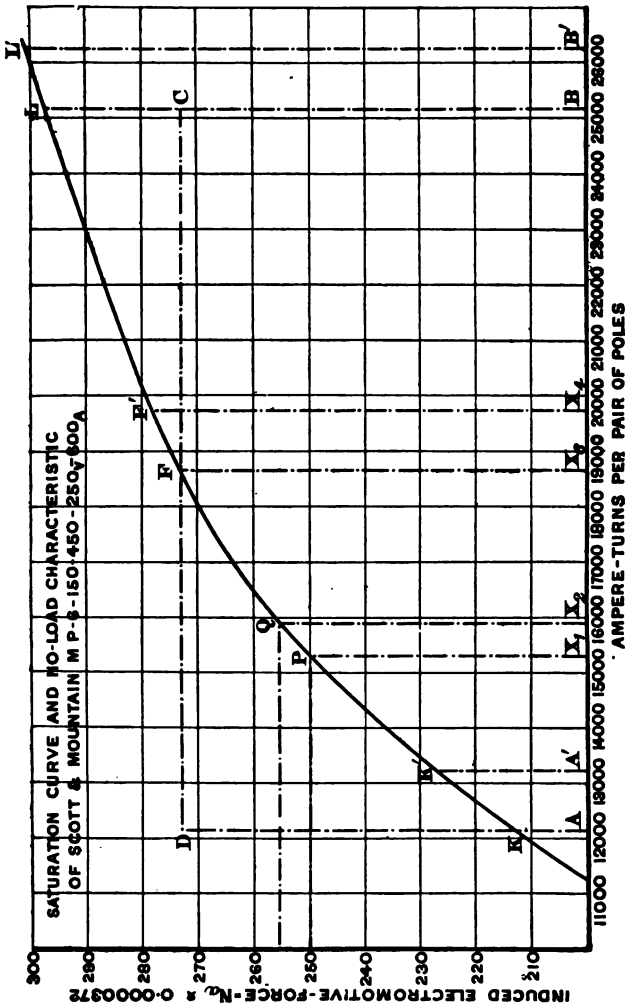


FIG. 56.—PREDETERMINATION OF SATURATION CURVE OF SCOTT AND MOUNTAIN  
6-POLE, 150 KW. DYNAMO.

Finding this point on the scale of ordinates of the curve and projecting it across we find the point  $X_2$  on the scale of abscissæ, which corresponds to the ampere-turns required per pair of poles at full-load if armature reaction were entirely absent. This makes  $X_2 = 15,900$ .

Now, the number of slots lying between the pole-tips is

$$\frac{60 - 43}{360} \times 124 = 5.8$$

and in each slot there are four conductors carrying 100 amperes at full-load. Hence the demagnetizing turns of the armature at full-load, and upon the assumption that the brushes are moved right under the pole-tips, are

$$5.8 \times 4 \times 100 = 2320.$$

Multiplying this number by  $\nu$ , the necessary compensating ampere-turns per pair of poles are therefore

$$2320 \times 1.17 = 2715.$$

Adding, then, these ampere-turns to  $X_2$  we find  $X_3 = 18,615$  as the ampere-turns necessary at full-load, assuming that there were no drop of pressure due to the diminished permeability of the teeth at the forward pole-horn, due to distortion of the flux. But this is not the case. We must therefore allow for this as explained on page 129.

For this we have:—

$$\left. \begin{array}{l} \text{Ampere-turns} \\ \text{under one pair poles} \end{array} \right\} = \frac{47}{360} \times 124 \times 4 \times 100 = 6500.$$

We set off, therefore, 6500 ampere-turns on each side of the point  $X_3$  upon the scale of abscissæ, and obtain thus the points A and B, which represent the hindward and forward pole-horns respectively. If distortion of the main flux were absent, the latter would be proportional to the area A B C D. But as this is not so, it is proportional to the smaller area A B L K. In order to make this area equal to that of the rectangle, we

must shift the point F higher up the curve to the position F', so that

$$\text{Area } A' B' L' K' = \text{area } A B C D.$$

In this manner we obtain the point  $X_4$  as the necessary ampere-turns at full-load.

Their value is

$$X_4 = 19,700.$$

Comparing our calculated results with the actual values of the running machine, we have:—

Output.	Calculated Values.	Actual Values.
At no-load . .	15,300	14,800
At full-load .	19,700	17,800

The discrepancy between the values calculated from the drawings and the values found by the makers, is probably due to the quality of iron actually used being better than that assumed in the calculations.

The full-load excitation is made up as follows:—

Shunt-turns per pair of poles, 3602 carrying 4·10 amperes.

Series-turns per pair of poles, 5 carrying 600 amperes.

Total ampere-turns per pair of poles:—

$$3602 \times 4 \cdot 1 = 14,800 \text{ shunt ampere-turns.}$$

$$5 \times 600 = \underline{3,000} \text{ series ampere-turns.}$$

$$\therefore \text{Total ampere-turns} = \underline{\underline{17,800}}$$

#### LOSSES.

##### I. Copper Loss:—

###### Armature.

$$\begin{aligned} w_{ca} &= 600 \times 600 \times 0 \cdot 004 \\ &= 1440 \text{ watts.} \end{aligned}$$

###### Series Coils.

$$\begin{aligned} w_{cs} &= 600 \times 600 \times 0 \cdot 00083; \\ &= 298 \text{ watts;} \end{aligned}$$

$$\therefore w_s = 1738 \text{ "}$$

2. *Iron Loss.*—The number of cubic inches of iron in the teeth is:—

$$1 \cdot 625 \times 0 \cdot 396 \times 9 \times 124 = 720 \text{ cubic inches.}$$

The frequency of reversal of magnetism is:—

$$3 \times 450 \div 60 = 22 \cdot 5 \text{ cycles per second.}$$

At full-load the flux-density is 130,000 lines per square inch. Reference to the curve (page 13) shows that at 130,000 lines per square inch, and taking  $\eta$  (the hysteretic constant) as 0·003, which is a probable value for armature stampings, the hysteresis loss will be about 0·038 watts per cubic inch of iron at 1 cycle per second. Hence the hysteresis loss in the teeth is:—

$$720 \times 0 \cdot 038 \times 22 \cdot 6 = 620 \text{ watts.}$$

Similarly, on reference to the curve of eddy-current losses on page 15, we find that, at this flux-density, the eddy-current loss for 1 cubic inch of iron at 1 cycle per second for plates of 20 mils thickness is 0·00024 watts. Now the stampings of this armature are only 18 mils thick, therefore the eddy-current loss in the teeth is:—

$$720 \times 0 \cdot 00024 \times (22 \cdot 5)^2 \times \frac{(0 \cdot 018)^2}{(0 \cdot 020)^2} = 70 \text{ watts;}$$

making a total iron-loss in the teeth of 690 watts.

The number of cubic inches of iron in the armature core-body is:—

$$\{(29 \cdot 75)^2 \times 0 \cdot 78 \times 9\} - \{(18)^2 \times 0 \cdot 78 \times 9\} \\ = 3905 \text{ cubic inches.}$$

At full-load the flux-density is about 69,000 lines per square inch. From the curves, taking as before the hysteretic constant as  $\eta = 0 \cdot 003$ , we find that 0·013 watts are lost per cubic inch of iron at 1 cycle per second. Hence, the hysteresis loss in the core-body is:—

$$3905 \times 0 \cdot 013 \times 22 \cdot 6 = 1140 \text{ watts.}$$

For the eddy-current loss, we find that at this flux-density, and at 1 cycle per second, and for stampings 20 mils thick,

0.00008 watts are lost, so that the eddy-current loss in the core-body will be:—

$$3905 \times 0.00008 \times (22.5)^2 \times \frac{(0.018)^2}{(0.020)^2} = 128 \text{ watts,}$$

making the total iron-loss in the core-body 1268 watts.

Adding together the losses in the teeth and core-body, we have as the total iron-loss of the machine:—

$$w_i = 1958 \text{ watts.}$$

3. *Excitation Loss.*—The total resistance of the shunt winding is 61 ohms, therefore the current through the shunt-coils at full-load is—

$$\begin{aligned} \frac{250}{61} &= 4.1 \text{ amperes,} \\ w_x &= 4.1 \times 250 \\ &= 1025 \text{ watts.} \end{aligned}$$

4. *Commutator Losses.*—Upon the commutator are pressed twenty-four brushes (4 per pole), and the area of each brush is about 1.75 square inches, making a total area of brush contact of 42 square inches. The 600 amperes go in through 21 square inches and come out through the other 21 inches.

Assuming the contact resistance to be 0.03 ohm per square inch, we have for the  $C_2R$  loss at the commutator:—

$$\begin{aligned} 2 \times 600 \times 600 \times 0.03 \div 21 \\ = 1032 \text{ watts.} \end{aligned}$$

The peripheral speed of the commutator is 2275 feet per minute.

Assuming brush pressure to be 1.5 pounds per square inch and the friction coefficient to be 0.3, we have for the friction of the commutator

$$\begin{aligned} \frac{1.5 \times 0.3 \times 42 \times 2275 \times 746}{33,000} \\ = 1000 \text{ watts.} \end{aligned}$$

Hence the full-load loss by brush resistance and friction is

$$w_b = 2032 \text{ watts.}$$

5. *Friction and Ventilation Losses.*—Owing to this being a rope-driven machine the friction losses will come out rather high, say 3 per cent. of the output, that is

$$w_f = 4500 \text{ watts.}$$

The total full-load loss is obtained by taking the sum of the separate losses, that is

$$\begin{aligned} w &= w_e + w_i + w_x + w_b + w_f; \\ &= 1738 + 1958 + 1025 + 2032 + 4500; \end{aligned}$$

or, in total, 11,253 watts; say 11·25 kilowatts.

Therefore the full-load efficiency is:—

$$\eta = \frac{150}{(150 + 11\cdot25)} = 93 \text{ per cent.}$$

*Probable Heating.*—(a) Armature. From the drawings the heat-radiating surface of the armature is found to be about 2500 square inches.

The peripheral speed is

$$\frac{33 \times 3\cdot1416 \times 450}{12} = 2835 \text{ feet per minute.}$$

The watts lost in the armature at full load are:—

Iron loss	.	.	.	.	.	1958
Copper loss	.	.	.	.	.	1440

making the watts wasted per square inch of radiating surface

$$\frac{3398}{2500} = 1\cdot36 \text{ watts per square inch.}$$

A reference to the lower curve of Fig. 22 shows that the temperature-rise per watt per square inch, for a peripheral speed of 2835 feet per minute, is for large well-ventilated armatures 25 deg. C.

Hence we have

$$\theta_a = 25 \times 1\cdot36 = 34 \text{ deg. C.}$$

(b) Field-magnet system. Here the radiating surface is about 342 square inches per bobbin, or a total of 2052 square inches. The watts lost in the shunt coil have been already

estimated at 1025, and the watts lost in heat in the series winding are

$$(600 \times 600 \times 0.00083) = 298 \text{ watts.}$$

Hence the probable rise of temperature of the field coil is

$$\frac{(1025 + 298) \times 75}{2052}$$

$$\theta_m = 49 \text{ deg. C.}$$

(c) Commutator. For the probable heating of this part of the machine we have (page 120)

$$\theta_o = \frac{46.5 \times 2032}{21 \times 3.14 \times 9.5 (1 + 0.0005 \times 2275)}$$

$$\theta_o = 35.8 \text{ deg. C.}$$

*Sparking.*—We have already found the value of the cross-magnetizing ampere-turns, namely,

$$X_o = 6500$$

The ampere-turns required for the gap and teeth at full-load are about 16,700, the flux-density in the former being 65,000.

Hence the flux-density under the entrant pole-horn is approximately

$$65,000 \times \frac{16,700 - 6500}{16,700} = 39,700 \text{ lines per square inch,}$$

which is amply sufficient for commutation (see page 159).

Applying the sparking criteria described on page 159. Taking the formulæ there given, we find the present data are

$$B_s = 65,000$$

$$X_o = 570$$

$$K = 248$$

$$k_s = 2$$

$$g' = 0.31$$

$$d = 33$$

whence  $Y_1 = 65,000 \times 2 \div 570 = 228.$

$$Y_s = 248 \times 0.31 \div 33 (1 + 2) = 0.78$$

Thus  $Y_1$  and  $Y_2$  are both above the minimum values prescribed on page 159, and we may assume that the machine will not spark.

Fig. 57 gives the test-curves of the performance of this machine running on the testing-bed of the factory.

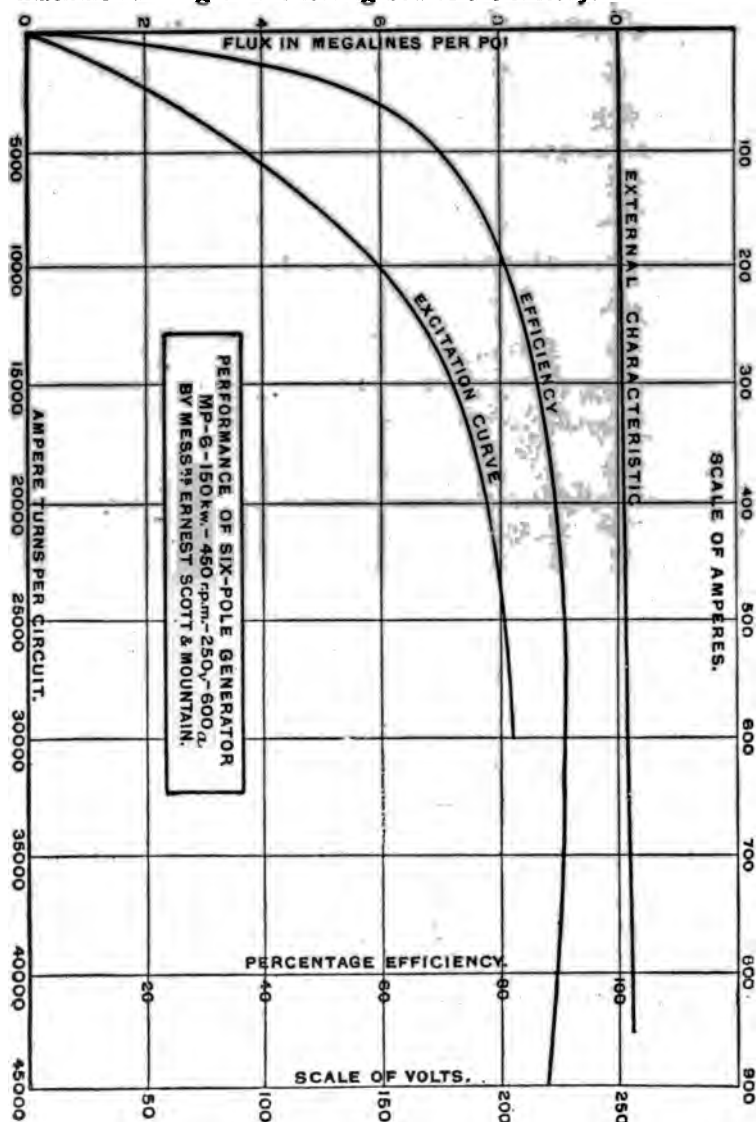


FIG. 57.—FACTORY TESTS OF SCOTT AND MOUNTAIN 6-POLE GENERATOR.

*Example II.*—OVER-COMPOUNDED MULTIPOLAR TRACTION GENERATOR WITH SLOTTED DRUM ARMATURE.

Built by The Walker Manufacturing Company.

M P—10—440—85—550 volts—800 amperes.

The leading dimensions and data given below and in Figs. , 59 and 60, have been kindly placed at the disposal of the thor by Mr. S. H. Short, formerly the company's chief engineer.

*General Specification.*

Full-load kilowatts	.	.	.	.	440
“ terminal volts	.	.	.	.	550
“ amperes	.	.	.	.	800
No-load terminal volts	.	.	.	.	500
Revolutions per minute	.	.	.	.	85
Peripheral speed, feet per minute	.	.	.	.	2000
Number of poles	.	.	.	.	10
Nature of load	.	.	.	.	Traction

*Dimensions (in inch units).*

Armature—

Core-disks, external diameter	.	.	.	.	90
“ internal “	.	.	.	.	68
Number of slots	.	.	.	.	464
Depth of slot	.	.	.	.	1.75
Width “	.	.	.	.	0.3
Pitch “ (average)	.	.	.	.	0.6
Depth of iron in core	.	.	.	.	9.25
Gross length of core	.	.	.	.	18.5
Iron “ “	.	.	.	.	13.8
Total number face conductors	.	.	.	.	1856
Conductors per slot	.	.	.	.	4
Style of winding	.	.	.	.	Parallel
Dimensions of conductor, bare	0.06	×	0.71		
“ “ “ insulated	0.08	×	0.75		
Section of conductor	.	.	.	.	0.0426
Mean length, one turn	.	.	.	.	103

*Field-magnets.*

Diameter of bore . . . . .	91
Polar angle . . . . .	27°
Turns per pair of poles, shunt . . . . .	2200
"    "    "    series . . . . .	19
Mean length, one shunt turn . . . . .	79
"    "    "    series " . . . . .	78
Diameter shunt conductor, bare . . . . .	0·162
"    "    "    insulated . . . . .	0·185
Section (square inches) . . . . .	0·0206
Dimensions series conductor, bare . . . . .	5 of 0·75 × 0·28
Dimensions series conductor, insulated . . . . .	5 of 0·79 × 0·32
Section of series conductor . . . . .	5 × 0·21
Shunt current at no-load . . . . .	10·7
"    "    full-load . . . . .	11·8

*Commutator.*

Diameter . . . . .	70
Useful length . . . . .	8·5
Number of segments . . . . .	928
Bars per brush . . . . .	3·3
Brushes per pole . . . . .	3
Size of brushes . . . . .	$\frac{3}{4} \times 2\frac{1}{2} \times 2\frac{1}{2}$
Area at commutator face . . . . .	1·95

In this machine, which is a representative type of tramway generator, the wrought-iron magnet-cores are cast in with the magnet-yoke, and are of square section. The pole-horns are secured to the poles after the field bobbins have been slipped on. The series winding is not wound over the shunt winding, but in a separate compartment of the bobbin, as may be seen from the section of the latter given in Fig. 59. The armature slots are quite straight with slightly rounded corners, and of width equal to the average width of tooth. There are four ventilating

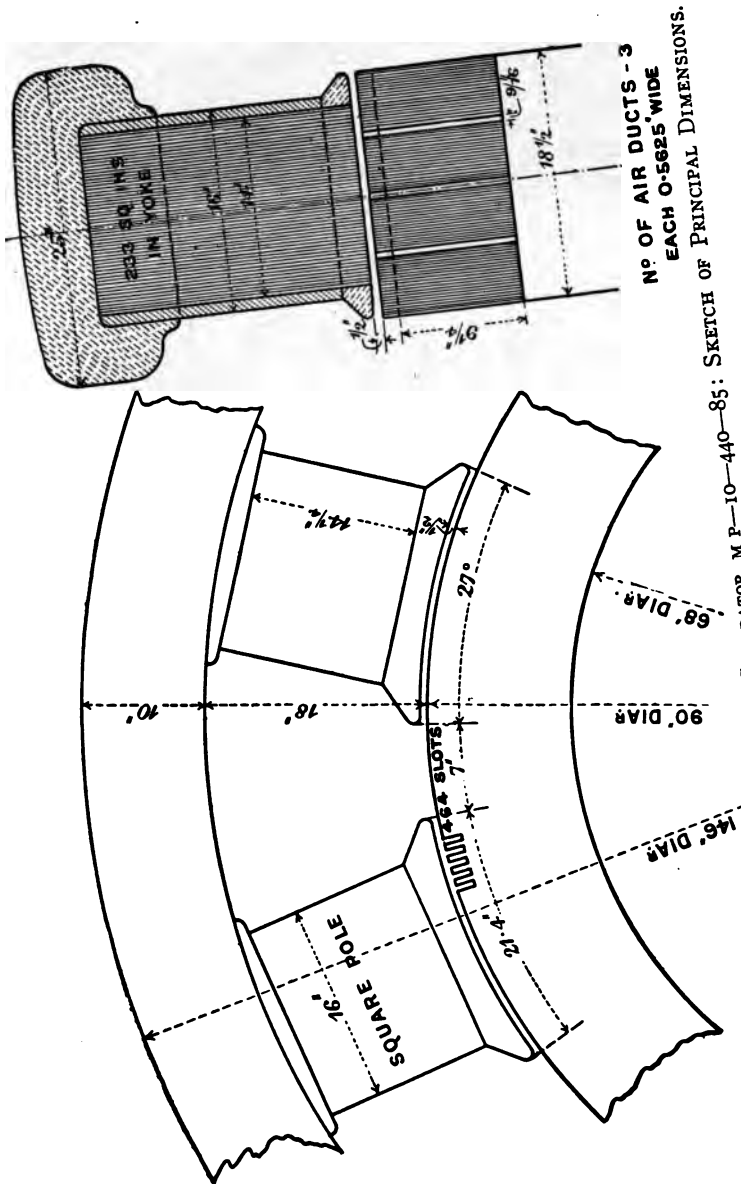


FIG. 58.—WALKER COMPANY'S TRACTION

ducts in the armature, each 0.5625 inch wide, while the paper insulation between the core-disks deducts 15 per cent. from the gross section of the core. The ratio of nett length to gross length of armature iron is thus 0.745. There are ten parallel circuits in the armature, and ten sets of carbon brushes at 36 degrees apart around the commutator.

The design of this machine may now be analysed in pre-

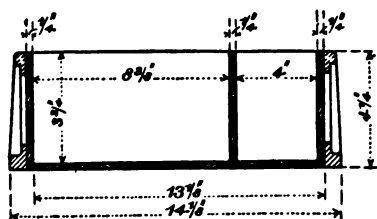


FIG. 59.—DIMENSIONS OF BOBBIN.

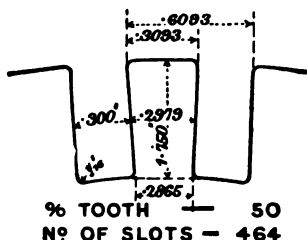


FIG. 60.—DIMENSIONS OF SLOTS.

cisely the same manner as in the last case. The first thing to do is to construct the saturation curve and no-load characteristic. We have

$$E = \frac{85}{60} \times 1856 \times N_a \times 10^{-8};$$

$$E = 0.0000263 \times N_a.$$

The dispersion coefficient of this machine has been determined experimentally by the makers, and found to be 1.13 and nearly independent of the load. Hence

E	$N_a$	$N_m$
460	17,500,000	19,750,000
500	19,000,000	21,500,000
520	19,750,000	22,300,000
560	21,300,000	24,900,000
580	22,000,000	24,900,000
600	22,800,000	25,800,000

From Fig. 58 and the data already given above, we obtain

Length of mean magnetic path in—

Magnet yoke	.	.	.	.	50
Two magnet cores	.	.	.	.	35
Armature core	.	.	.	.	33
Two teeth	.	.	.	.	3.5
Two air-gaps	.	.	.	.	1

And for the magnetic areas—

For the yoke	.	.	.	$25 \times 9.32 = 233$ sq. in.
“ magnet cores	.	.	.	$16 \times 16 = 256$ “
“ armature core	.	.	.	$9.25 \times 13.8 = 128$ “

The actual number of teeth under one pole is

$$464 \times \frac{27}{360} = 34.8.$$

As the air-gap is on the whole large compared with the diameter of the armature, and as the teeth are worked at high flux-densities, the flux will spread considerably, and for this reason we will take the number of teeth transmitting the flux as being 37. The average pitch of the slots is 0.6, and their width 0.3 inch. Hence the area of the teeth is

$$37 \times (0.6 - 0.3) \times 13.8 = 154 \text{ square inches.}$$

Also, owing to the high densities in the teeth, and the rounded corners of the latter, the area of the air-gap will be very nearly the same as that of the pole-face. This latter is

$$\frac{91 \times 3.1416 \times 27 \times 18.5}{360} = 397 \text{ square inches.}$$

This figure would adequately represent the air-gap area if there were no ventilating ducts in the armature core. Reducing the polar area obtained above in the proportion of the length without ducts to the length of pole-face, we obtain

$$\text{Area of air-gap} = \frac{397 \times 16.25}{18.5} = 348 \text{ square inches.}$$

The two tabulations below give the working out for two points of the saturation curve, namely, when  $E = 520$  and  $E = 560$ . The tooth flux-densities given are the true values, obtained from the apparent values by means of curve A A of Fig. 7. The values of ampere-turns per inch ( $\delta$ ) have been obtained from the magnetization curves of Plate I.

$$E = 520; N_a = 19,750,000; N_m = 22,300,000.$$

Part of Machine	Material.	Magnetic Length.	Magnetic Area.	Flux-density.	Values of $\delta$ (from Curve).	Ampere-turns.
Yoke . .	cast iron	50	233	47,600	92	4600
Two magnet cores }	wrought iron	35	256	87,000	28.5	1000
Two air gaps	air	1	348	56,700	[0.3133]	18,100
Two teeth .	iron stampings	3.5	154	123,000	700	2450
Armature core	"	33	128	77,000	8	264
Total ampere-turns per pair of poles						26,414

$$E = 560; N_a = 21,300,000; N_m = 24,000,000.$$

Part of Machine.	Material.	Magnetic Length.	Magnetic Area.	Flux-density.	Values of $\delta$ (from Curve).	Ampere-turns.
Yoke . .	cast iron	50	233	51,400	115	5750
Two magnet cores }	wrought iron	35	256	93,600	45	1575
Two air-gaps	air	1	348	61,100	[0.3133]	19,200
Two teeth .	iron stampings	3.5	154	131,000	1400	4900
Armature core	"	33	128	83,000	11	365
Total ampere-turns per pair of poles						31,790

In the same way we calculate other points of the curve, obtaining

When $E = 460$ ,	necessary ampere-turns =	20,710
" = 500	" "	= 24,040
" = 580	" "	= 34,960
" = 600	" "	= 39,100

By plotting the curve connecting these six points we obtain the working part of the no-load characteristic, as shown in Fig. 61. We have then

Necessary ampere-turns at no-load =  $X_1 = 24,250$ .

We will now proceed to find the necessary ampere-turns at full load. These will be greater than those required at no-load by an amount depending upon—

- (1) Amount of over-compounding asked for.
- (2) The value of the full-load lost volts.
- (3) Amount of armature demagnetization.
- (4) " " distortion.

Now there are 1856 conductors in series round the whole armature, that is, 928 turns. From the data already given (p. 42), we thus have for  $40^\circ \text{ C.}$

$$r = \frac{9.2 \times 928 \times 103}{12 \times 0.0426 \times 10^8} = 1.72 \text{ ohms}$$

and the resistance of the armature at this temperature is thus

$$r_a = \frac{1.72}{4 \times (5)^2} = 0.0172 \text{ ohms.}$$

There are 19 turns of series conductors per pair of poles, the mean length of one turn being  $(78 \div 12) = 6.5$  feet. Hence the total resistance of the series winding at  $40^\circ \text{ C.}$  is

$$\begin{aligned} r_m &= \frac{9.2 \times 6.5 \times 19 \times 5}{1.05 \times 1,000,000} \\ &= 0.00542 \text{ ohm.} \end{aligned}$$

Hence the total resistance of the main current circuit in the machine is  $(0.0172 + 0.0054) = 0.0226 \text{ ohm.}$  The full-load drop is therefore

$$e = 800 \times 0.0226 = 18.1 \text{ volts.}$$

Now the terminal pressure of the machine at full load is to be 550, corresponding to an over compounding of 10 per cent. Hence the armature must generate at full load  $(530 + 18.1) = 548.1$  volts. Finding this point on the scale of ordinates of the curve, and projecting it across, we find the point

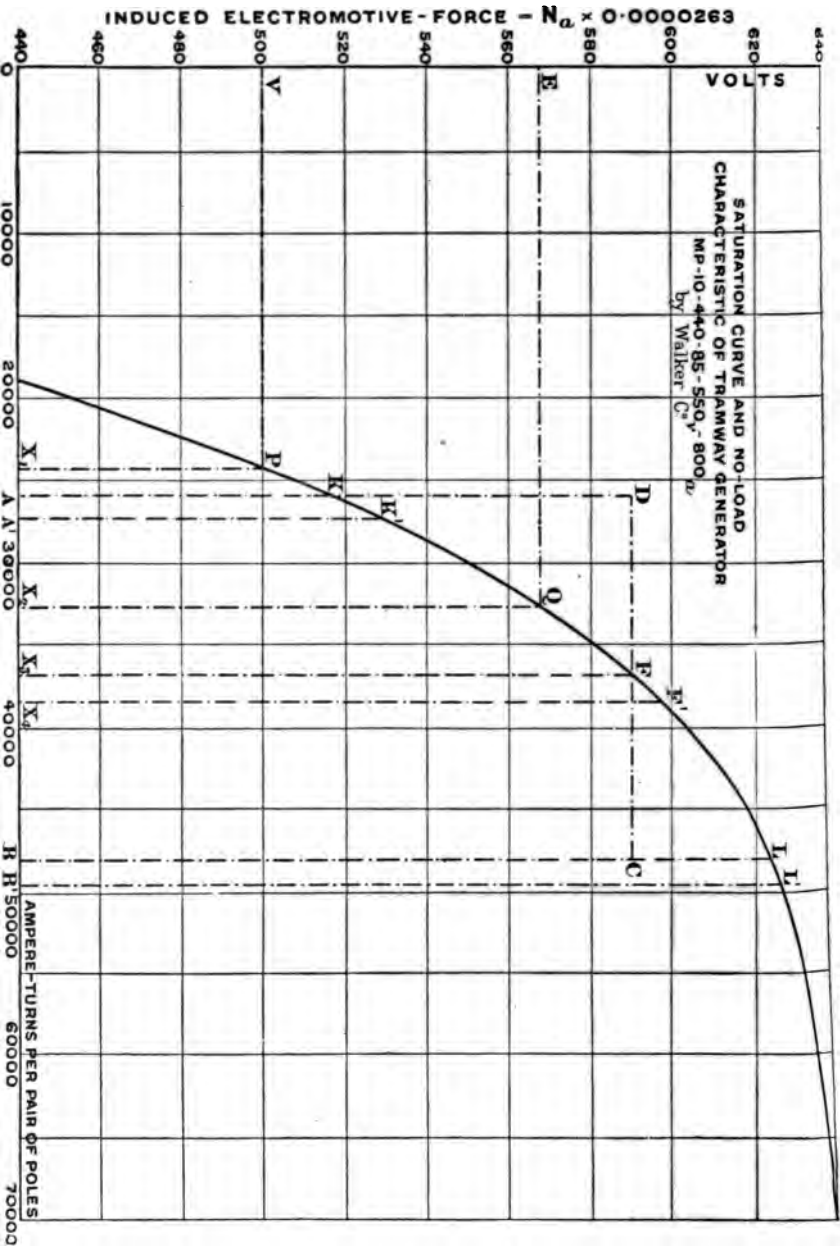


FIG. 61.—SATURATION CURVE OF WALKER 10-POLE GENERATOR.

$X_2$  on the scale of abscissæ, which corresponds to the ampere-turns required per pair of poles at full load if armature reaction were entirely absent.

Now the number of slots lying between the pole-tips is

$$\frac{(36 - 27)}{360} \times 464 = 11.5$$

and in each slot there are four conductors carrying a little over 80 amperes at full load. Hence the demagnetizing turns of the armature at full load, and upon the assumption that the brushes are moved right under the pole-horns, are

$$11.5 \times 4 \times 80 = 3680.$$

The compensating ampere-turns per pair of poles are therefore

$$3680 \times 1.13 = 4160.$$

Adding then these ampere-turns to  $X_2$ , we find  $X_3$  as the ampere-turns necessary at full-load, assuming that there is no drop of pressure due to the diminished permeability of the teeth at the forward pole-horn, due to distortion of the flux. But this will not be the case, owing to the high flux-densities in the armature teeth. We must therefore allow for this as explained on p. 129. For this we have:—

$$\left. \begin{array}{l} \text{Ampere-turns under} \\ \text{one pair poles} \end{array} \right\} = \frac{27}{360} \times 464 \times 4 \times 80$$

$$= 11,100.$$

We set off, therefore, 11,100 ampere-turns from each side of the point  $X_3$  upon the scale of abscissæ, and obtain thus the points A and B, which represent the backward and forward pole-horns respectively. If distortion of the main flux were absent, the latter would be proportional to the area A B C D. But as this is not the case, it is proportional to the smaller area A B L K. In order to make this area equal to that of the rectangle, we must shift the point F higher up the curve to the position F', so that

$$\text{area A' B' L' K'} = \text{area A B C D}.$$

In this manner we obtain the point  $X_4$  as the necessary ampere-turns at full load. Their value is

$$X_4 = 38,500.$$

Comparing our results with the actual values of the running machine we have—

Output.	Calculated Values	Actual Values.
At no-load . .	24,250	23,600
At full-load .	38,500	41,200

Showing that the calculated value is about  $2\frac{1}{2}$  per cent. too high at no load, and  $6\frac{1}{2}$  per cent. too low at full load, which is good enough. Had the magnetic properties of the iron used for this machine been definitely known, a somewhat better result might have been obtained.

*Calculation of Full-Load Efficiency.*—

(1) *Copper loss.* This is

$$w_c = 800 \times 800 = 0.0226$$

$$w_c = 14,500.$$

(2) *Iron loss.* The weight of iron in the teeth is

$$\begin{aligned} 1.75 \times 0.3 \times 13.8 \times 464 \times 0.28 \\ = 944 \text{ pounds.} \end{aligned}$$

The frequency of reversal is

$$\frac{85}{60} \times 5 = 7.1 \text{ periods per second.}$$

They are worked at a flux-density of about 132,000 lines per square inch at full load. From the curves of Fig. 2, p. 10, we see that at a flux-density of 80,000 lines per square inch and a frequency of 30 the hysteresis watts per pound are about 2.1, and the eddy loss 0.8 watt per pound. Therefore the hysteresis loss in the teeth is

$$\begin{aligned} \frac{944 \times 2.1 \times 7.1 \times (132000)^{1.6}}{30 \times (80000)^{1.6}} \\ = 1040 \text{ watts.} \end{aligned}$$

And the eddy-current loss in the teeth is

$$\frac{944 \times 0.8 \times (7.1)^2 \times (132,000)^2}{(30)^2 \times (80000)^2} \\ = 115 \text{ watts,}$$

making a total iron loss in the teeth at full load of 1155 watts.

The weight of the armature core is

$$\left( \frac{86.5 + 68}{2} \times 3.1416 \times 128 \right) \times 0.28 \\ = 8750 \text{ pounds.}$$

At full load it is worked at a flux-density of about 85,000 lines per square inch. From the curves of iron-loss we see that at 30 periods per second and at this flux-density the hysteresis loss is about 2.3 watts per pound, and the eddy-current loss 0.9 watt per pound. Hence the hysteresis loss in the core is

$$8750 \times 2.3 \times \frac{7.1}{30} = 4760 \text{ watts.}$$

And the eddy-loss is

$$8570 \times 0.9 \times \frac{(7.1)^2}{(30)^2} = 440 \text{ watts.}$$

So that the total iron-loss in the core is 5220 watts. Adding this to the loss in the teeth we have as the total iron-loss of the generator at full load

$$w_i = 6375, \text{ say } 6380 \text{ watts.}$$

(3) *Excitation loss.* There are 2200 shunt-turns per pair of poles. Taking the previously calculated value of full-load ampere-turns, we have as the shunt current at full load

$$\frac{38,500 - (19 \times 800)}{2200} = 10.6 \text{ amperes.}$$

Hence

$$w_x = 10.6 \times 550 = 5840 \text{ watts.}$$

(4) *Commutator loss.* There are altogether 30 carbon brushes upon the commutator, the section of each at the commutator face being 1.95 square inches. The total area of contact is thus 58.5 square inches. Assuming the contact

resistance to be 0.03 ohms per square inch of contact area (p. 118) we have as the  $C^2 R$  loss at the commutator

$$2 \times 800 \times 800 \times \frac{0.03}{29.75} = 1320 \text{ watts.}$$

The peripheral speed of the commutator is

$$\frac{70 \times 3.1416 \times 85}{12} = 1560 \text{ feet per minute.}$$

Assuming the brush pressure to be 1.5 pounds per square inch, and that the friction coefficient is 0.3, we have as the friction loss of the commutator

$$\frac{1.5 \times 58.5 \times 1560 \times 0.3 \times 746}{33,000} = 930 \text{ watts.}$$

Hence the total loss by brush resistance and by friction is

$$w_b = 2250 \text{ watts.}$$

(5) *Friction and ventilation losses.* Taking these as 1 per cent. of the full-load output—an ample estimate—we have

$$w_f = 4400 \text{ watts.}$$

The total full-load loss is the sum of the five losses above, or

$$\begin{aligned} w &= w_c + w_t + w_x + w_b + w_f \\ w &= 33,390 \text{ watts.} \end{aligned}$$

Therefore the full-load efficiency is

$$\frac{440}{(440 + 33.9)} = 0.928$$

$$\eta = 92.8 \text{ per cent.}$$

*Probable heating.*—

(a) *Armature.* From the drawings the heat-radiating surface of the armature is found to be about 11,000 square inches. The peripheral speed is

$$\frac{90 \times 3.1416 \times 85}{12} = 2000 \text{ feet per minute.}$$

The watts lost in the armature at full load are

$$\begin{array}{lcl} \text{Iron-loss} & . & . \quad 6380 \\ \text{Copper-loss} & . & . \quad 800 \times 800 \times 0.172 = 11,000 \end{array}$$

making the watts wasted per square inch of radiating surface

$$\frac{17,380}{11,000} = 1.58 \text{ watts per square inch.}$$

A reference to the lower curve of Fig. 22 shows that the temperature-rise per watt per square inch for a peripheral speed of 2000 feet per minute is  $30^{\circ}$  C. Hence we have

$$\theta_a = 30 \times 1.58 = 47.5 \text{ deg. Centig.}$$

(b) Field-magnet System. Here the radiating surface is about 2000 square inches per bobbin, or a total of 20,000 square inches. The watts lost in the shunt coils have been already estimated at 5840, and the watts lost in heating the series winding are

$$(800 \times 800 \times 0.0054) = 3460 \text{ watts.}$$

Hence the probable rise of temperature of the field-coils is

$$\frac{(5840 + 3460) \times 75}{20,000}.$$

$$\theta_m = 35 \text{ deg. Centig.}$$

(c) Commutator. For the probable heating of this part of the machine we have (p. 120)

$$\theta_c = \frac{46.5 \times 2250}{70 \times 3.14 \times 8.5 (1 + 0.0005 \times 1560)}$$

$$\theta_c = 17.5 \text{ deg. Centig.}$$

*Sparking.*—We have already found the value of the cross-magnetizing ampere-turns, namely,

$$X_c = 11,100.$$

The ampere-turns required for the gap and teeth at full-load are about 25,000, the flux-density in the former being

about 61,000. Hence the flux-density under the entrant pole-horn is approximately

$$61,000 \times \frac{25,000 - 11,000}{25,000} \\ = 34,000 \text{ lines per square inch,}$$

which is a sufficient value for sparkless reversal.

Applying the two *criteria* of sparking (p. 159), we have the following data:—

$$\begin{aligned} B_s &= 19,000 \text{ lines per square inch;} \\ d &= 90 \text{ inches diameter of core;} \\ K &= 928 \text{ total segments of commutator;} \\ k_2 &= 3 \cdot 3 \text{ number of segments of commutator short-circuited at once;} \\ g &= 0 \cdot 5 \text{ inches across gap;} \\ X_0 &= 1856 \times 80 \div 90 \pi = 525 \text{ ampere-conductors per inch at full-load;} \end{aligned}$$

whence we get:

$$\begin{aligned} Y_1 &= 19,000 \times 3 \cdot 3 \div 525 = 119; \\ Y_2 &= 928 \times 0 \cdot 5 \div 90 (1 + 3 \cdot 3) = 1 \cdot 2. \end{aligned}$$

Now for a sparkless result (see p. 159) in this class of machine the conditions are that  $Y_1$  should not be *less* than 38, nor  $Y_2$  less than 1·2. From both points of view, therefore, the criterion is satisfied by the design. As a matter of fact, the machine runs quite sparklessly with adjusted brushes; and even with *fixed* brushes runs nearly sparklessly at all loads up to 25 per cent. overload.

We may now proceed to describe a number of modern designs by various makers who have kindly furnished data and drawings to the Author.

*Oerlikon Co.'s Dynamos.*—For many years past the Oerlikon Machine Works near Zurich have produced excellent machines. Till 1892 the chief designer was Mr. C. E. L. Brown. After that date Mr. Kolben and, later, Dr. Behn Eschenburg, have been amongst those mainly responsible for the types produced. With the Oerlikon works originated the multipolar type of generator of which Fig. 62 is an example,

a type which since 1890 has been extensively followed in the United States as well as in Great Britain.

Plate III. shows an Oerlikon MP 4—265—370 machine. The general aspect is given in Fig. 62. Of this pattern a 450-volt generator is at work in the Central London Railway, and a 550-volt one at Zurich. Both machines are identical in

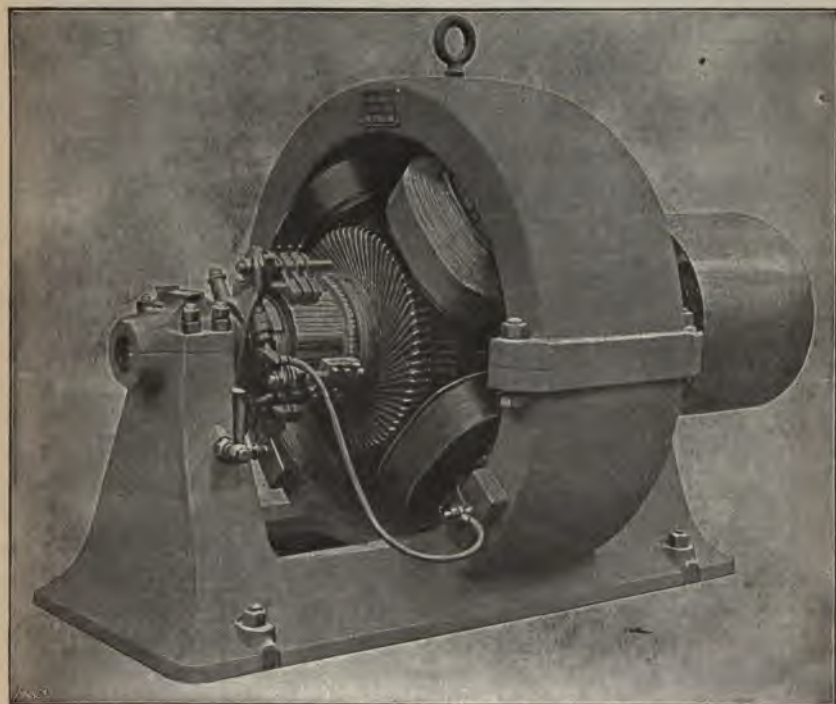


FIG. 62.—TYPICAL 4-POLE GENERATOR OF THE OERLIKON WORKS.

all respects except as to the number of slots and conductors, corresponding to the different voltages.

The yoke is of cast steel, the diameter over yoke being 75 inches, and the length of yoke parallel to shaft is 17·3 inches. The four field-coils each have, in the 550-volt machine 3200 turns, and in the 450-volt machine 2600 turns, the diameter of the shunt-wire in the former case being 0·079 inch, and in the latter 0·087 inch. The higher voltage machine,

that is to say, the Zurich generator is compounded, there being  $3\frac{1}{2}$  turns of strip copper conductor on each pole this conductor measuring 0·138 inch by 6·75 inches insulated. The pole-pitch is 31·5 inches, the pole-pieces being rectangular, length parallel to shaft 19·3 inches, and pole-arc 23·6 inches. The length of air-gap in both machines is 0·49 inch. The diameter of armature is 39·4 inches, length over conductors 26·8 inches, and length between core heads 19·7 inches; there being one ventilating duct in the armature 0·98 inch wide.

The machine for Zurich has 240 slots and 480 conductors each 0·114 inch by 0·925 inch, the slots being 0·256 inch wide and 1·02 inch deep; and in the machine for London there are 208 slots and 416 conductors each 0·138 inch by 1·04 inch, the slots being 0·335 inch wide and 1·18 inch in depth. The winding in both machines is a four-circuit doubly re-entrant winding (symbol  $\odot$ ) with four sets of brushes and four parallel paths through the armature. The commutator is 22·8 inches in diameter, there being 240 segments in the Zurich machine and 208 in the London machine, the length of segment being about 9 inches.

Plate IV. shows an Oerlikon traction generator MP 12—500—100—550 volts—900 amperes. A general view of the machine is afforded by Fig. 63.

This machine, of which two were constructed for the Basel tramways, was required to fulfil somewhat unusual conditions which were specified as follows:—

When taking the undermentioned amounts of power the electric output of a generator shall be as follows:—

Horse-power (metric)	.	.	120	300	500	750
Kilowatts output	.	.	77·8	206	347	510
Volts at terminals	.	.	550	550	550	550
Revolutions per minute	.	.	100	100	100	96

[This allows for a 4 per cent. drop in the engine-speed at top load.]

The generators must be able to develop an output of 347 kilowatts for a continuous run of 18 hours without the temperature rise in any part exceeding 35° C. They must be able

to endure an exceptional overload up to 520 kilowatts for two hours, and a temporary one up to 675 kilowatts. Mechanically

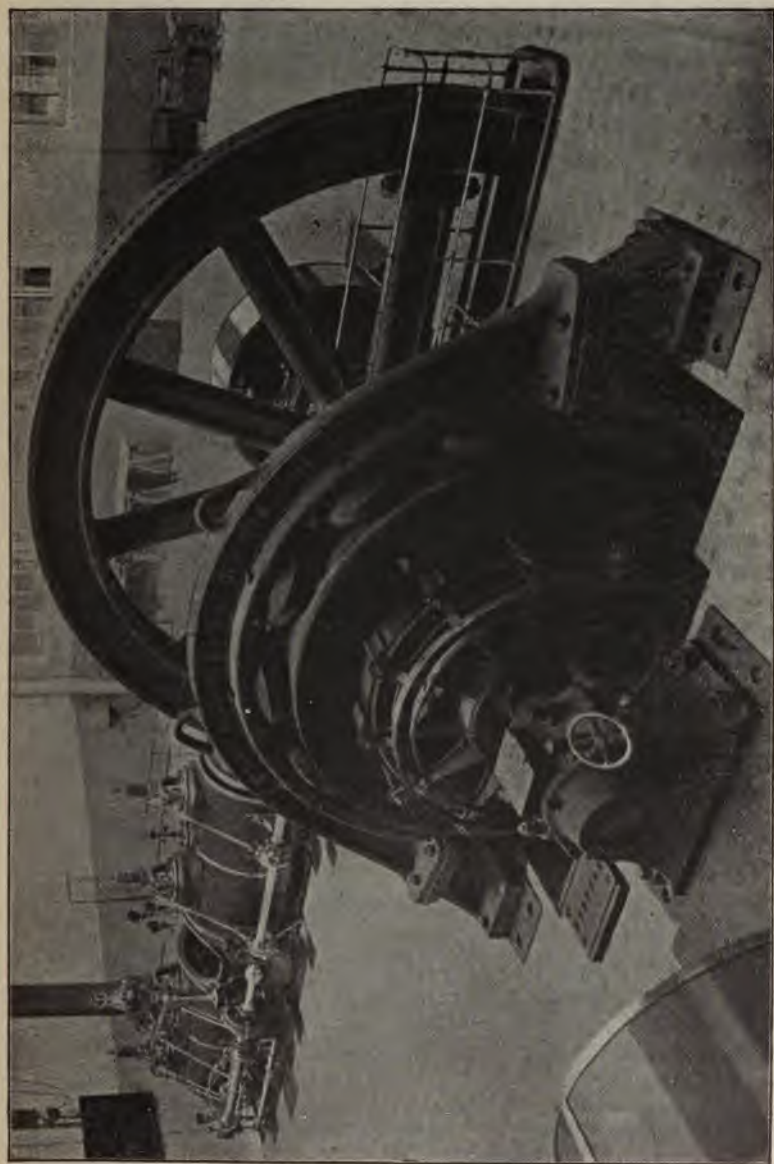


FIG. 63.—OERLIKON CO.'S 12-POLE GENERATOR, MP 12—500—100—550v—900 A., AT BASEL.

they must be able to stand a casual doubling of the speed, and electrically must stand a test of 2000 volts between winding and frame. At a constant speed and with a fixed position of the handle of the exciter rheostat, the voltage shall rise from 550 to 588 volts, or shall fall to 512 volts when the load of the machine being at first 250 horse-power, shall be respectively reduced to zero or raised to 500 horse-power. If the speed of the steam engine is raised or lowered 3 per cent. the resulting change of voltage shall not be greater than 12 per cent. Each generator is a pure shunt machine.

This generator, which represents the normal type "G 120" of the Oerlikon Company, has the following principal dimensions:—The diameter of the armature is  $98\frac{1}{4}$  inches, the length between core-heads  $14\frac{1}{4}$  inches, and there is a single ventilating duct about 0.8 inch wide. There are 1326 conductors each 0.472 by 0.138 inch, two such being placed in each of 663 slots; each slot being 0.236 inch wide and 1.18 inch in depth. The gap-space is 10 millimetres or 0.3937 inch. The core-segments are mounted on a cast-iron spider. The winding is a series-parallel wave with six circuits from brush to brush, the winding-step being  $y_1 = y_2 = 111$ . This reduces the number of conductors to half that which would have been necessitated had a parallel winding (12-pole, 12-circuit) been adopted. The commutator is composed of 663 segments of hard-drawn copper built up upon a cast-iron ring, and the commutator risers connecting the segments with the winding are of iron. The commutator is about 71 inches in diameter and has an active length of 6 inches. There are 12 ranges of carbon brushes with 6 brushes in each range, mounted on a bronze support. The yoke of cast steel, bored on its inner face, is cast in two parts. The 12 pole-cores are cylindrical, of cast steel, with a diameter of 13.825 inches. Their basal faces are turned off to fit the bored face of the yoke, and each is secured with two screws. The shunt-coils on the bobbins consist each of 950 turns of a wire 0.141 inch in thickness. The steel yoke is stiffened by a single rib of girder section. It will be noted that the pole-cores are in this machine relatively short. The whole magnet-frame stands on two feet at the sides upon

two cast-iron foot-steps which are secured into the concrete foundation. The front bearing is screwed down to a separate

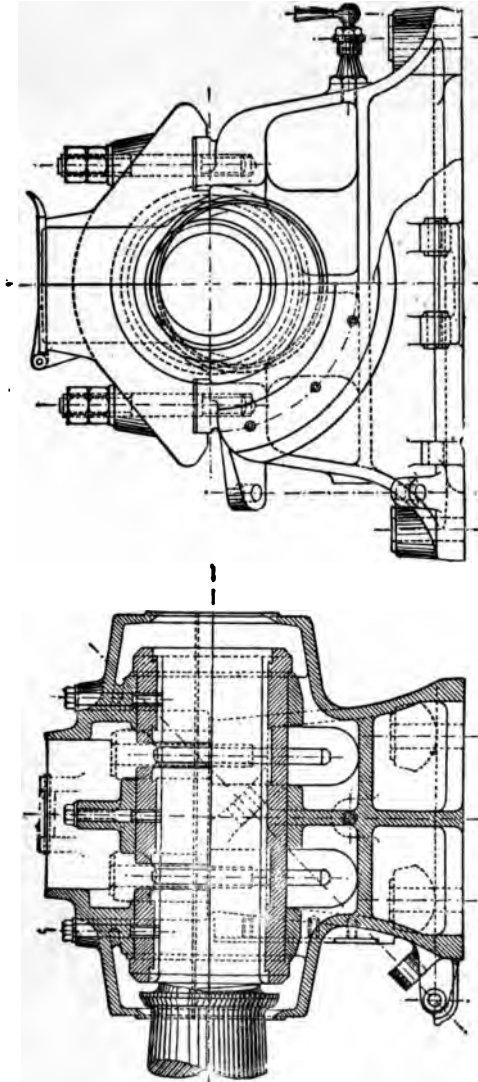


FIG. 64.—BEARING OF OERLIKON 12-POLE GENERATOR.

foot-step. The design of these bearings is separately shown in Fig. 64. They are provided with oil-rings for automatic lubri-

cation. The weight of the magnet-frame and pole-cores is about  $9\frac{1}{4}$  tons, with about  $1\frac{1}{2}$  tons of copper in the twelve mag-

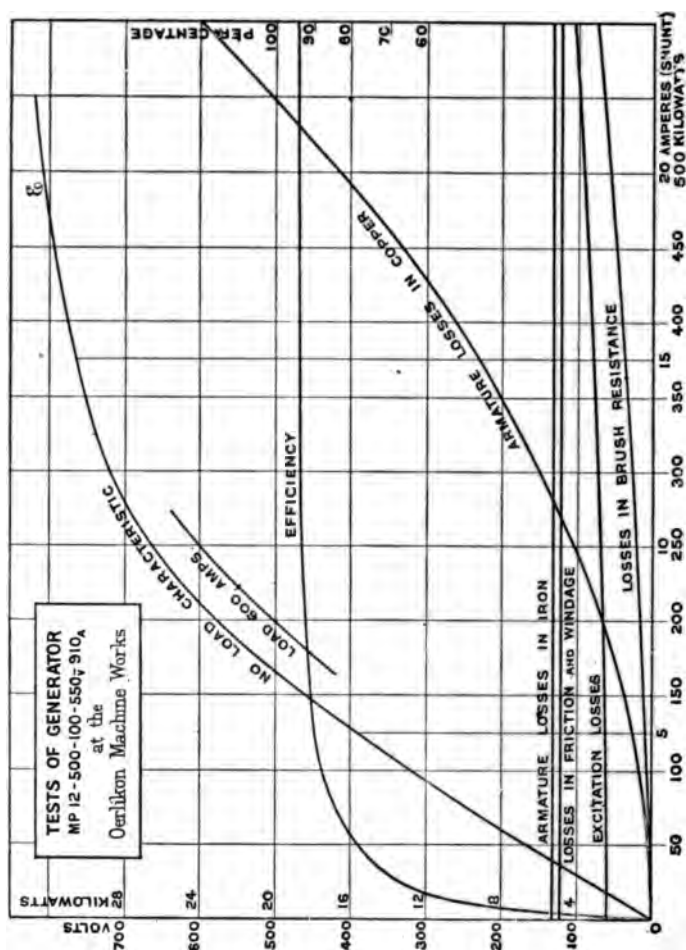
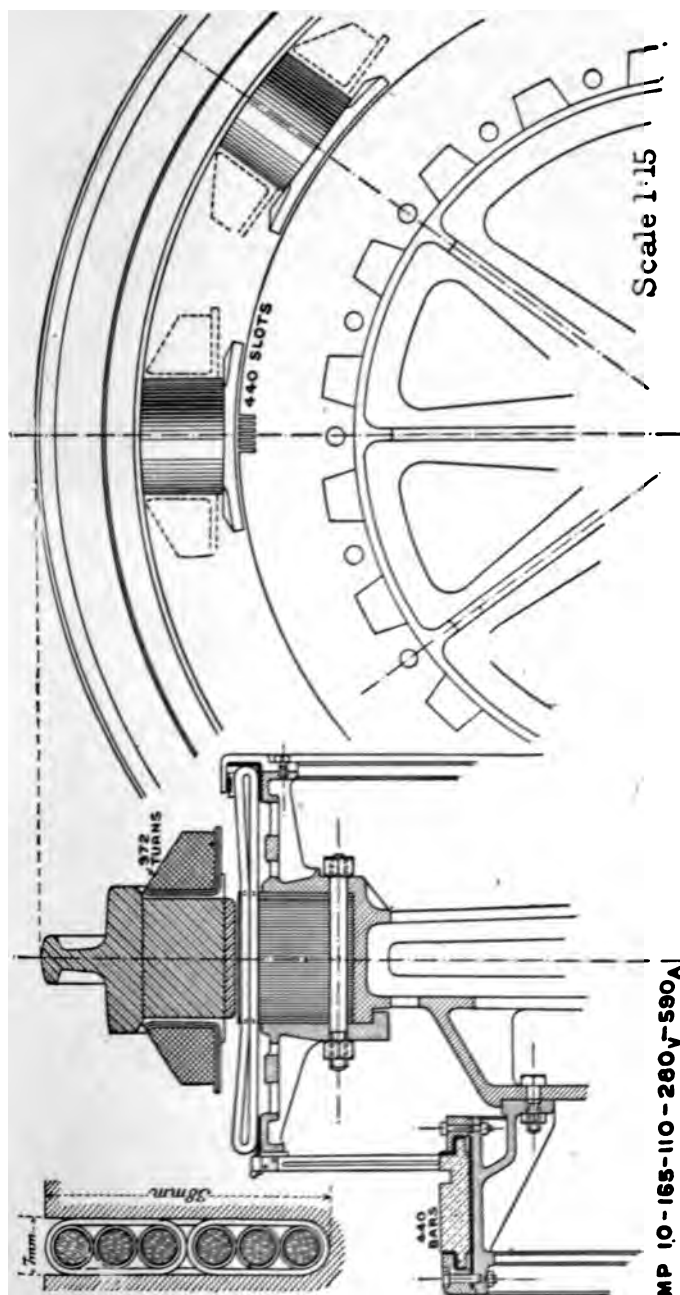


FIG. 65.—TESTS OF OERLIKON 12-POLE GENERATOR.

net-bobbins. The armature weighs about  $11\frac{1}{2}$  tons; there being about  $4\cdot7$  tons of iron stampings,  $1320$  lb. of copper conductors and  $880$  lb. of commutator segments.

Tests made on the completed machines show the following



MP 10-165-110-260V-590A

FIG. 66.—OERLIKON CO.'S 10-POLE LIGHTING GENERATOR.

results. Shunt winding resistance 38 ohms, armature resistance (brush to brush) 0.02 ohm. Efficiency at all loads from 350 to 500 kilowatts about 94 per cent. The temperature-rise after 12 hours at full-load was about 25° C. At all loads, and even with sudden changes of 300 to 1000 amperes, and with fixed position of brushes, the machines were reported to show no sparks at the commutator. Fig. 65 gives a graph of these tests and shows the no-load characteristic of the machine.

Another recent Oerlikon machine is shown in Fig. 66, which is a lighting generator supplied to Bordeaux. This is M P 10—165—110—280 volts—590 amperes. It has 440 slots with six conductors in each slot, the coils being former-wound with three conductors in the upper and three in the lower half of the coil. The commutator has 440 segments. The coils are joined up as a lap-winding, the end of one to the beginning of the next, and each junction is united by an inverted butterfly evolute riser to two segments of the commutator situated 88 segments apart (corresponding to the double pole-pitch), thus tending to equalize the currents to be collected at the brushes. The dimensions of the slot are 1.497 by 0.295 inch. The magnets are shunt-wound, with all ten coils in series; each coil having 972 turns of a wire 0.131 inch in diameter covered to a diameter of 0.150 inch. The no-load flux is 5.8 megalines. The efficiency is 90 per cent. from half-load to full-load. Steinmetz coefficient 2.24. Ampere-conductors per inch, 660.

A large electrolytic generator, furnished by the Oerlikon Company to the Aluminium works at Rheinfelden, is shown in Fig. 67.

In this machine, M P 32—560—55—80 volts—7000 amperes, the large number of poles is necessitated by the very large current output and slow speed. The pole cores are cast solid with the yoke of cast steel, no pole shoes being used. The Steinmetz coefficient in this machine works out to 5.1, the figure being high as the result of the low speed. The armature is 177 inches, or 14 feet 9 inches in diameter, the length between core-heads being 16.2 inches, the ratio of diameter of armature to length being very large. The armature is par-

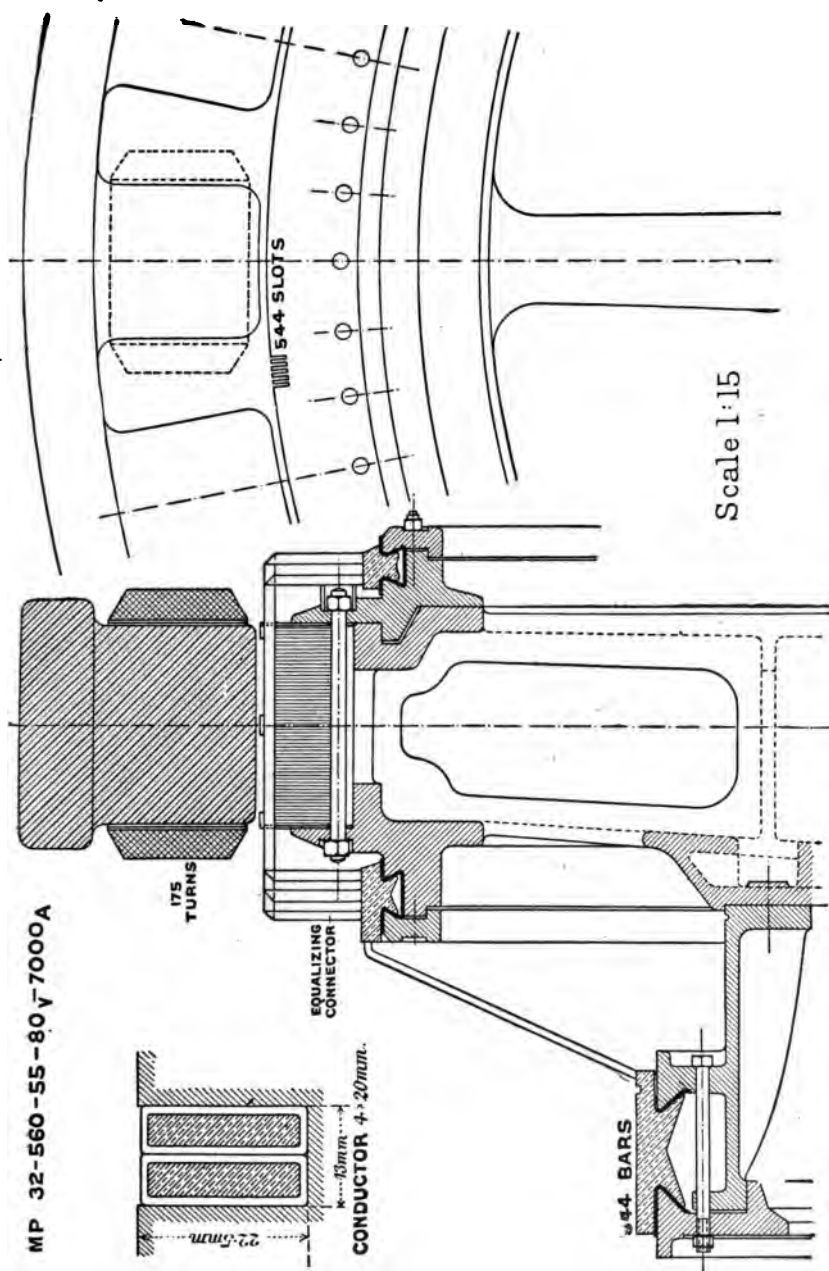


FIG. 67.—OERLIKON Co.'s 32-POLE ELECTROLYTIC GENERATOR AT RHEINFELDEN.

allel-wound with 32 parallel circuits, so that the current in one conductor is 225 amperes; the end connexions at both ends of the armature are made of evolutes terminating in copper segments, held exactly as the segments in an ordinary commutator by end clamping plates.

This construction enables a set of equalizing conductors to be added at the commutator end of the armature, as shown in the figure. There are 544 slots in the armature, there being two conductors per slot, each conductor having a cross-sectional area of 0.124 square inch, the slots being 0.885 inch in depth and 0.51 inch wide. The commutator is 118 inches in diameter, and has 544 segments, each segment being 13 inches in length; it is bracketed out from the armature spider. There are 32 sets of brushes with 12 brushes per set. The field-bobbins are connected in two parallels of 16 bobbins in series, each bobbin having 175 turns of copper wire 0.374 inch in diameter, wound in 7 layers of from 28 to 22 turns per layer. The flux per pole at no-load is 8.03 megalines.

Fig. 68 shows an Oerlikon generator M P 6—285—450—90 to 190 volts—1500 amperes, supplied to the Volta Electrochemical Company at Rome.

This machine has cast steel poles bolted on, the pole-core and pole-shoe forming a single casting. The poles are slotted radially with a very large single slot about 4.7 inches long and 1.97 inches wide, this slot being, of course, provided to prevent distortion of the pole-face flux, this precaution being especially necessary in this machine, owing to the fact that very heavy currents are carried per unit length of periphery, the ampere-conductors per inch periphery working out to 835 at the full-load rated output of 1500 amperes; which is large for a 6-pole machine. The yoke is 62½ inches in diameter over all; the armature is 35½ inches in diameter, and has 187 slots, each slot being 1.44 inches deep and 0.258 inches wide. There are in each slot two conductors of 0.093 square inch section, the current through each conductor being 250 amperes, there being thus 500 amperes to be collected at each set of brushes. The armature has a lap-drum six-circuit wind-

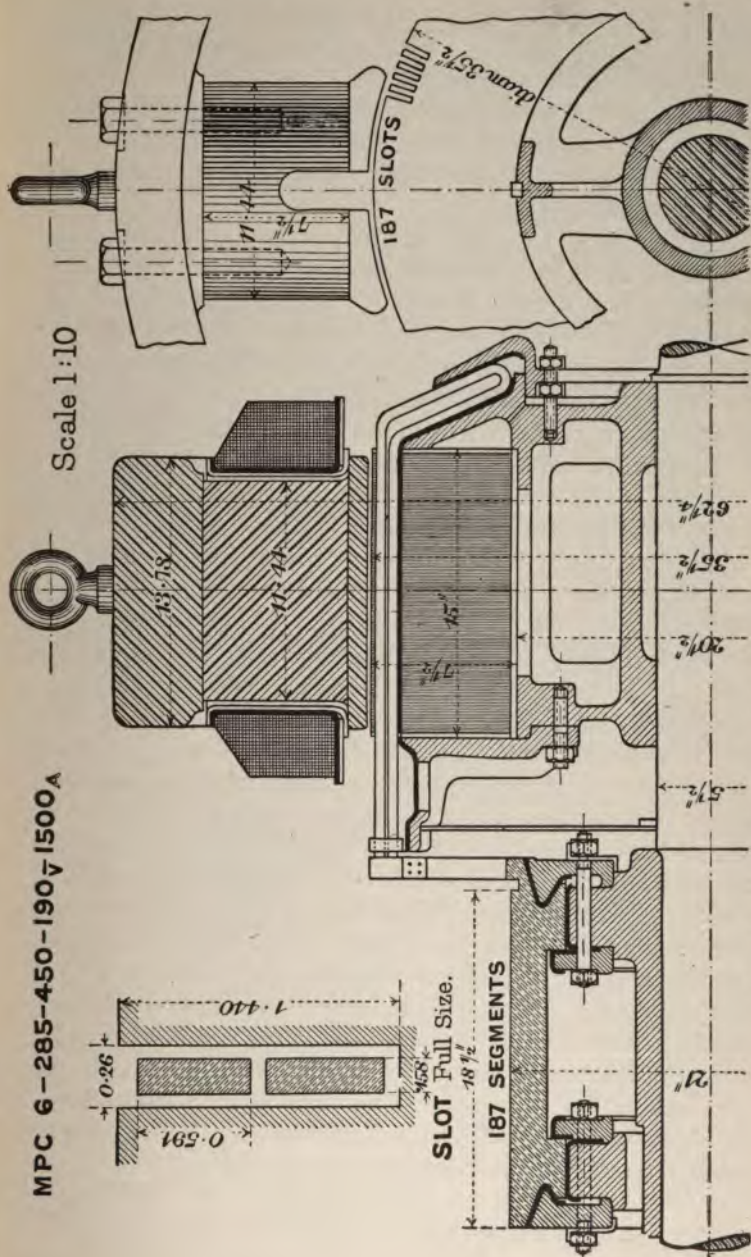


FIG. 68.—OERLIKON Co.'s 6-POLE ELECTROLYTIC GENERATOR AT ROME.

ing, the end loops of the former-made conductors being bent down and held in place by an end-clamping shield. The commutator is 21 inches in diameter and of very massive construction, the segments being securely held at both ends and clamped in the manner plainly shown in the drawing. The field-coils have each 600 turns of wire of 0·189 inch diameter bare and 0·204 inch insulated.

Messrs. Scott and Mountain make a standard line of generators from a 12-pole 78-inch by 13-inch generator of 280 kilowatts and 90 revolutions to a 4-pole 42-kilowatt machine at 680 revolutions, the larger sizes being, of course, for direct coupling, and the smaller ones rope-driven. These machines throughout are characterised by solid mechanical construction, the large relative size of bearings, in all sizes, being especially noticeable. The mechanical construction of the armature is simple, the armature laminations being held upon a spider by stout bolts. In the larger sizes, the commutator is bracketed out from the arms of the spider, and in the smaller sizes the commutator is built up on an extension of the armature hub, the whole being held against a shoulder on the shaft by a threaded ring kept home by a grub-screw. Slotted drum armatures and barrel-windings are used throughout; the pole-cores are of cast steel, while both cast-iron and cast-steel yokes are used, the former in the larger sizes. The armature conductors, instead of being bent round and in one continuous piece at the back of the armature, are clamped together with a copper clip and the whole then soldered, this construction being considered to give special advantages in repairing. In the machine having four conductors per slot (see Plate II.) the conductors are first taped, then a pair of them are wrapped with manila paper and placed in the slot, which again is lined with varnished milboard. In this particular example the total thickness of insulation between conductor and core is ·075 inch. In connecting to the commutator, the commutator-risers are let into the commutator-bars, and then both soldered and rivetted, thus making an excellent joint both mechanically and electrically. The bind-

ing-wires are insulated from the armature-core with one turn of varnished millboard and mica slips. The commutator con-

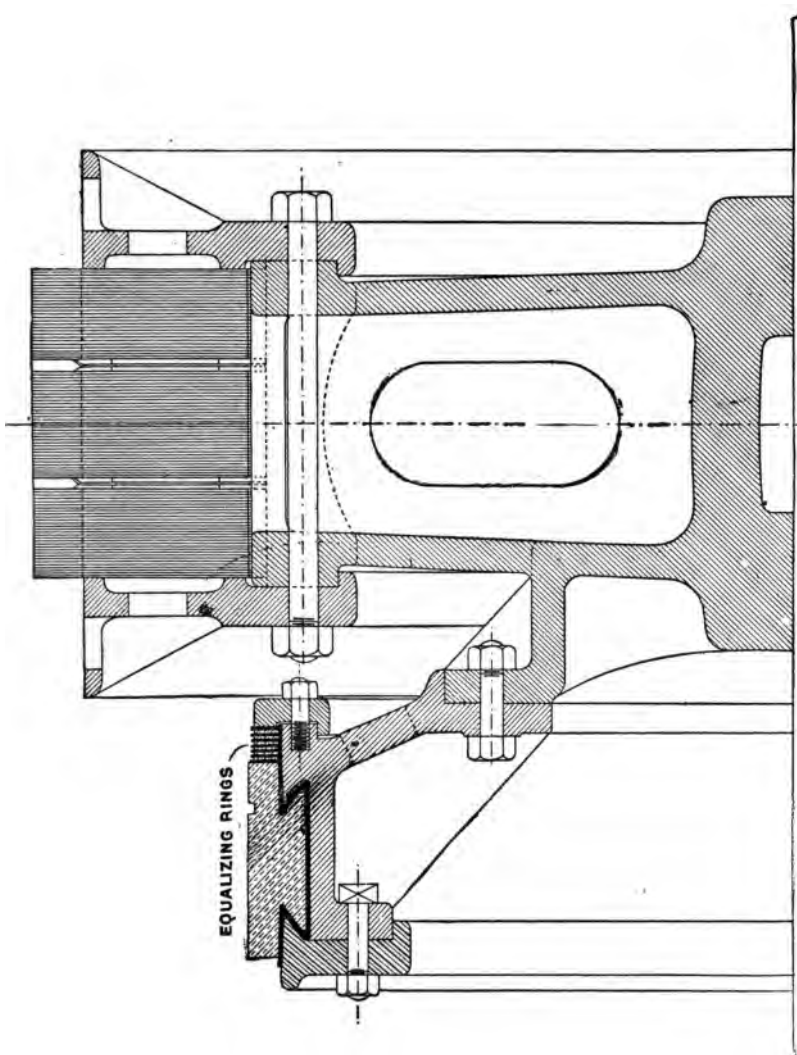


FIG. 69.—SCOTT AND MOUNTAIN MP 12—280—90, SHOWING EQUALIZING RINGS.

struction possesses no unusual features. Equalizing rings are used in the larger sizes, built up against the back of the commu-

tator, and held by a cast-steel clamping-ring. In a particular case of the 12-pole 28-kilowatt generator (see Fig. 69) equalizing rings, six in number are used, these rings being built up with the commutator, behind the commutator-risers, and insulated as shown. The six copper rings are 1 inch in depth and  $\frac{1}{8}$  inch thick, the insulation between the rings being 0.09 inch in thickness and the insulation at the ends  $\frac{1}{8}$  inch thick.

This firm aims at high flux-densities throughout, running the flux up to  $B = 140,000$  or more at roots of teeth and over 100,000 in the magnet-cores; and using also a fairly high gap density. The field-bobbin construction in these machines is a detail worthy of note. The bobbins are made with sheet-iron cores and thick teak flanges, which have a good appearance, but which would seem to take up a good deal of valuable space.

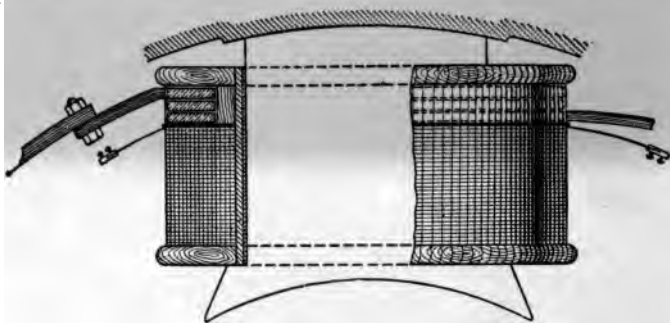
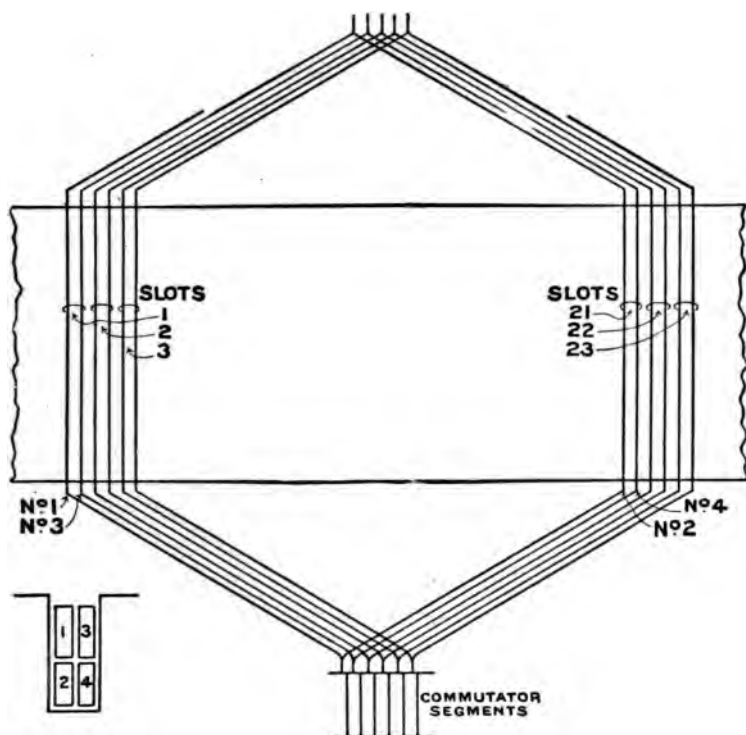


FIG. 70.—FIELD-MAGNET OF 6-POLE GENERATOR OF SCOTT AND MOUNTAIN.

Fig. 70 shows a detail drawing of bobbin construction for the Scott and Mountain 6-pole generator depicted in Plate II. For insulation over the sheet-iron cores two layers of varnished canvas and one complete layer of press-spahn 0.06 inch thick are used. According to the makers, the use of these sheet-iron cores, thus enabling the winding readily to communicate its heat to the frame of the machine, permits the use of very high current-densities in the field-bobbins. They are thus enabled to use current-densities of over 1000 amperes per square inch

in the field winding, and by thus shortening the necessary winding space, the over-all dimensions of the machine may be reduced, and consequently the cost.



**FRONT.** Join 1 (upper) in N°1 slot to 2 (lower) in N°21 slot  
**BACK.** " 2 (lower) " " 21 " " 3 (upper) " " 1 "  
**FRONT.** " 3 (upper) " " 1 " " 4 (lower) " " 21 "  
**BACK.** " 4 (lower) " " 21 " " 1 (upper) " " 2 "  
*and so forth*

FIG. 71.—WINDING DIAGRAM OF SCOTT AND MOUNTAIN  
6-POLE GENERATOR.

Fig. 71 shows the winding scheme of the 6-pole machine described, the design of which is analysed at the beginning of the present chapter, p. 160.

The compounding conductor is of rectangular strip, wound edgewise, as shown in the detail drawing. These coils are

wound bars, then opened out slightly and taped. Connexion of one series coil to another is made by flexible copper couplings bolted on. Carbon brushes are used throughout without exception in machines by this firm, the current density in the carbon being about 30 amperes per square inch in the larger machines and about 15 amperes in the smallest size. An extract from a very usual form of guarantee for these machines, supplied by the makers, is as follows:—There shall be no sparking due to variation of load within the limits of no-load and 25 per cent. overload, the machine to run continuously with practically no sparking or burning of the brushes, and without blackening the commutator. The machine to stand a momentary overload of 50 per cent. without sparking with fixed brushes, and the armature to stand an alternating potential of 2000 volts without damage.

Messrs. Brown, Boveri & Co., of Baden (Switzerland) have constructed many types of machines for continuous currents. A leading feature of most is the barrel-winding in two superposed cylindrical layers, patented in November 1892 by Mr. C. E. L. Brown.

Fig. 72 shows the normal type of belt-driven machine with cast-steel yoke, and steel pole-cores. All the larger sizes have laminated pole-shoes screwed on. In the case of compound machines the series and shunt-coils are separately former-wound, the series-coils being nearest the armature. The spider is of cast-iron; the core-disks insulated from one another. The binding wires are of bronze. The pole-cores are each secured by one central screw and a steady-pin.

In the Author's work on *Dynamo-electric Machinery* are given several other examples of the machines of Brown, Boveri & Co., including a large 8-pole electrolytic generator.

Fig. 73 depicts an interesting machine which departs from the normal type in one respect. It is a *double-current machine*; being furnished not only with the ordinary commutator to yield continuous currents, but also with three slip-rings, that it may at the same time furnish a three-phase alternating current. The rocker-ring is bracketed out from the yoke, while

the brushes for the slip-rings are supported from the pedestal of the bearing. The chief data of this machine, which was constructed for the lighting station at Alloa (Scotland), are as follows:—M P (cont. and 3-phase)—8—194—350—490 volts (or 300  $\Delta$  volts)—396 amperes. The armature core-body is 42·1 by 12·4 inches, with 128 slots 1·9 inch deep and 0·49 wide. In each slot are 12 conductors, four-deep,



FIG. 72.—BROWN, BOVERI & Co.'s NORMAL TYPE (1901).

each having a section 0·325 inch by 0·13 inch. The over-all length of the armature windings is about 25 inches. The gap is 0·355 inch. The magnet-cores are 7·9 inches in radial length, and 10·2 inches in diameter. The outside diameter of the yoke is 71·9 inches. The commutator is 32·4 inches in diameter, and the segments 6·9 inches gross length, there being 384 segments. The magnets are shunt-wound with 1820 turns on each bobbin, the wire being 0·083 inch in diameter. The space-factor in the slots is 0·315; that of the magnet-coils

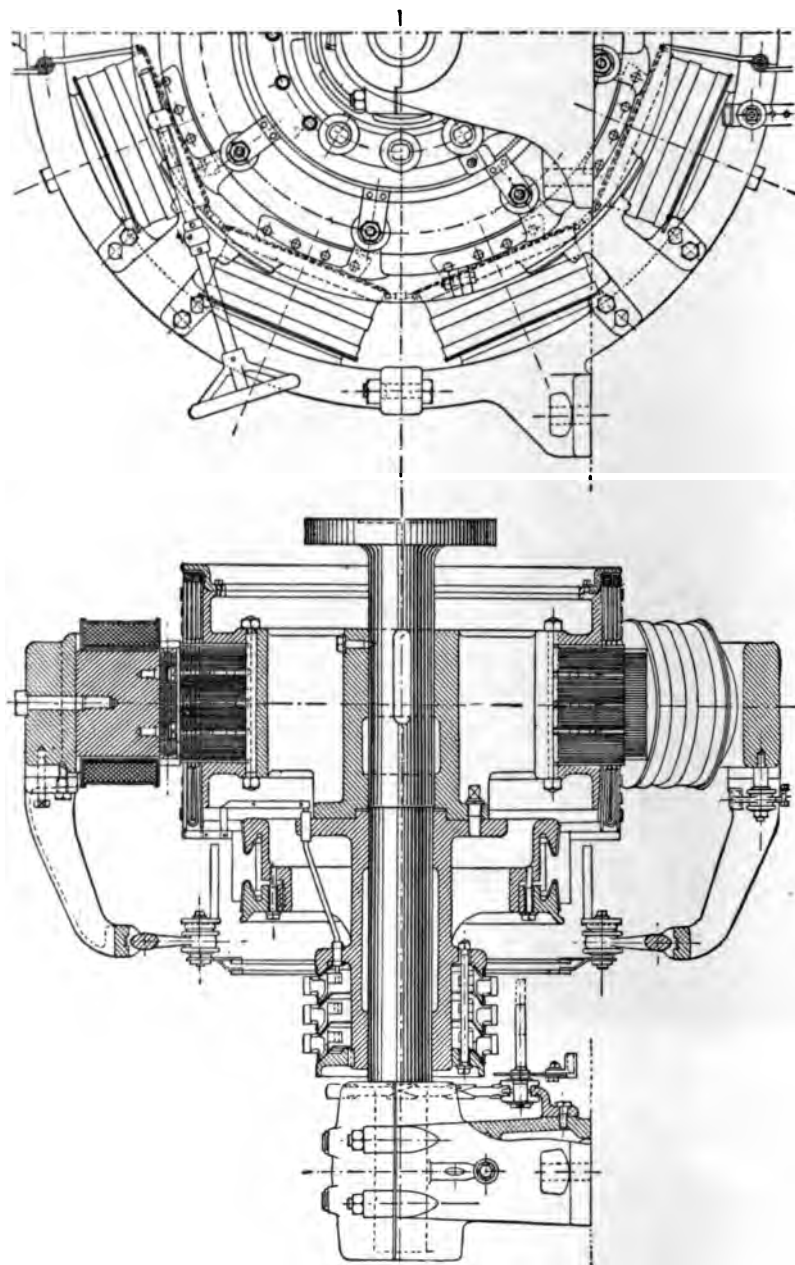


FIG. 73.—DOUBLE-CURRENT GENERATOR OF BROWN, BOVERI &amp; CO.

0.568. The current density in the armature is 1920; in the shunt-coil 962; at the brush contacts 40 amperes per square inch. The flux-density in the gap is 42,000, and in the teeth 116,000 at no-load. The no-load excitation is 6600 ampere-turns per pole, of which the gap and teeth require about 5360. The cross-magnetizing ampere-turns are about 6600, and the demagnetizing 3000. Ampere-conductors per inch of periphery 520.

Figs. 74 and 75 depict a specially interesting machine of Brown, Boveri & Co., for a high voltage. This is M P 4—20—700—1000 volts—20 amperes.

In this small machine, working at high pressure, great care is bestowed upon the question of insulation throughout the design. The chief data of this machine are as follows:—

Outside diameter of yoke 35 inches, length parallel to shaft 11.4 inches of cast-steel. The magnet-cores are circular in section, having a diameter of  $7\frac{1}{2}$  inches, and the cores, and at the same time the pole-pieces are attached to the yoke of the machine by a single steel bolt; the fact that the seatings both at the yoke and pole-pieces are turned and thus possess a rounded surface, making this possible. The armature is 15 inches in diameter, the length between core-heads being 9.85 inches. There are 59 slots and 1416 conductors; there being thus 24 conductors per slot, arranged in the slots in two taped sets of 12 conductors each. Round wire of a section of 0.0037 square inch bare and 0.0070 square inch insulated is used, and the total thickness of insulation between conductors and core amounts to 0.07 inch. The winding has a two-circuit series-parallel grouping, described on p. 102; and throughout great attention is given to the insulation of the end turns and connexions. But the design of the commutator is the most noteworthy feature of this machine. Owing to the fact that only twenty amperes have to be collected, the question of insulation was the paramount one to be considered. There are 177 segments, or three per slot; the end clamping plates of this commutator are usually substantial.

Mica 0.035 inch thick is used between the segments, and

the end insulating rings project far beyond the end of the segments, and are not turned off flush, as is usually the case with machines of lower voltage. On the whole the construction is very simple, that of the commutator especially so; the design being very open throughout and such that there is little chance

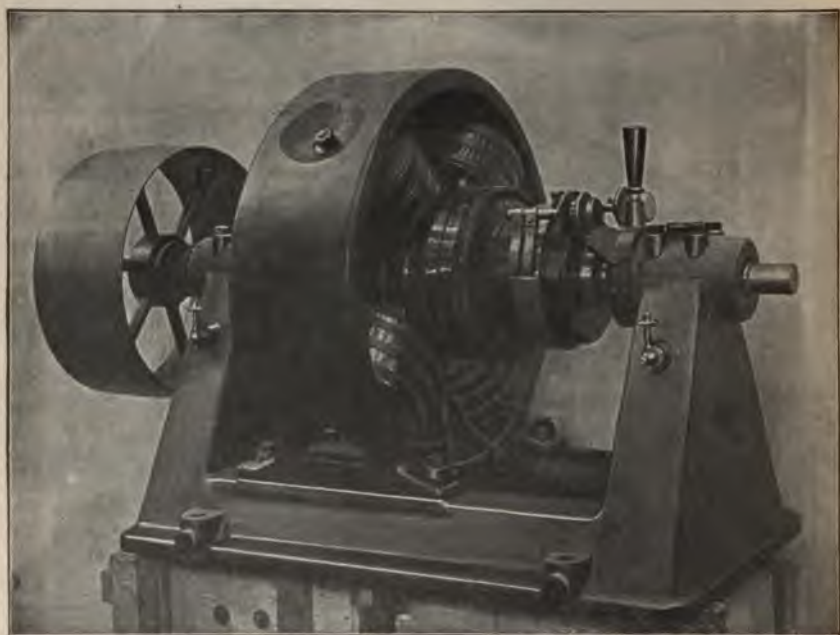


FIG. 74.—HIGH-VOLTAGE DYNAMO OF BROWN, BOVERI & CO.

of dust or dirt collecting, which might lead to a breakdown in the insulation. Fig. 75 gives a sectional view of the armature.

Of late Messrs. Brown, Boveri & Co. have designed special machines to be coupled direct to Parsons' steam turbines. The very high speeds have necessitated sundry modifications in design. The armatures are relatively smaller in diameter and of greater length, and the field-magnets are of the pattern devised by Deri<sup>1</sup> with his special mode of cross-compounding.

<sup>1</sup> See *Elektrotechnische Zeitschrift*, vol. xxiii. p. 817, September 1902.

These field-magnets are built up of concentric stampings with closed slots at the inner periphery, and wound in a manner re-

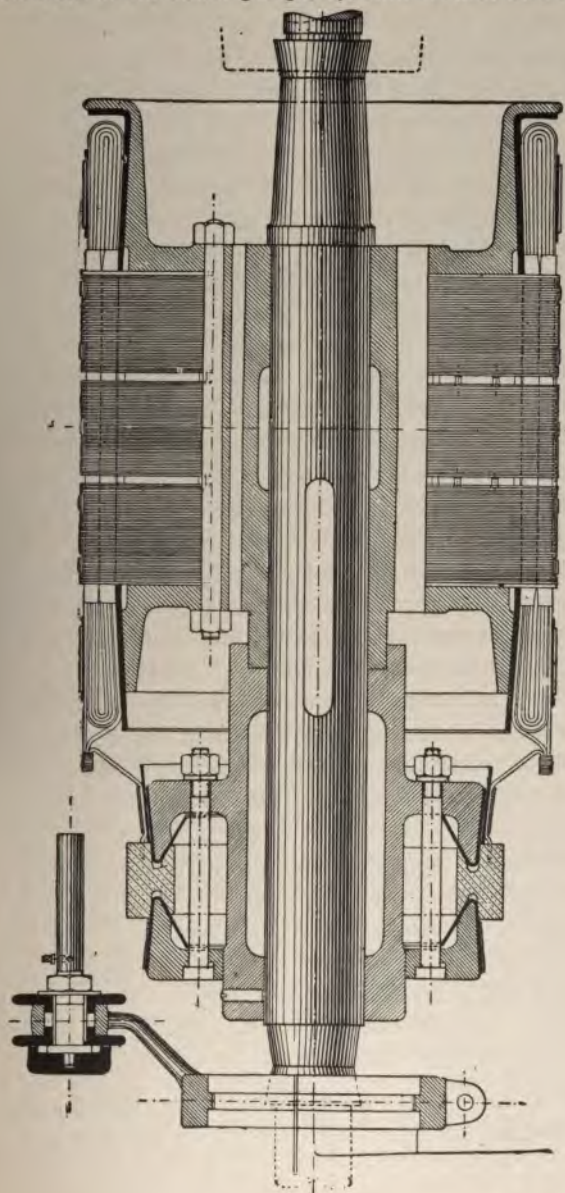


FIG. 75.—ARMATURE OF BROWN'S HIGH-VOLTAGE GENERATOR.

sembling the stator of a two-phase induction motor. Owing to the high peripheral speed carbon brushes cannot be used at the commutator.

The General Electric Company of Schenectady, with which is associated the British Thomson-Houston Company of Rugby, has produced many hundreds of machines for traction or lighting. So far back as 1893 it exhibited at the Chicago Exhibition a multipolar generator of 1500 kilowatts, having 12 poles and running at 75 revolutions per minute. This machine is described by Messrs. Parshall and Hobart in their work on *Electric Generators* (London, 1900), in which they give very full constructional data of this and of three other machines, viz. :—

M P 6—200—135—500 volts—400 amperes;

M P 10—300—100—125 volts—2400 amperes;

M P 6—250—320—500 volts—455 amperes.

Of the three, the second, which is a lighting machine, is not a satisfactory design, judged by modern standards; while the first is excellent. Its armature is lap-wound with 1760 conductors in two layers, in 220 slots, barrel-wound. The current-density is 1760 amperes per square inch in the armature, 6670 in the commutator risers, 800 in the shunt-coil, 770 in the series-coil, 44·5 at the brush contact. The flux-densities at full-load were as follows:—76,000 lines per square inch in armature core-body, 121,000 (apparent) in teeth, 45,000 in the gap, 96,000 in steel pole-core, 70,000 in steel yoke. The excitation percentages were allocated as follows:—

	At no-load.	At full-load
Armature core . . . . .	4·4	5·0
Teeth . . . . .	7·3	10·4
Gap . . . . .	58·9	63·0
Pole core . . . . .	17·3	21·5
Yoke . . . . .	12·1	14·0
Compensation for demagnetization . . . . .	..	24·4
“ distortion . . . . .	..	5·0
	100·0	143·3

The excitation at no-load required 7630 ampere-turns per pole; at full-load 10,990. The heat-loss in the armature was

1·70 watts per square inch of radiating surface, and the temperature rise 30° C. by thermometer or 37 by resistance measurement. The losses in percentage of the nett full-load output were :—armature iron 1·38, armature copper 4·4, commutator and brushes 0·735, excitation 1·21, including series-coils and rheostat. The curves given in Figs. 46 and 47 relate to this machine.

Other machines of the General Electric Company are described in the Author's *Dynamo-electric Machinery*, including a 6-pole 400 kilowatt belt-driven machine, and a 6-pole 150 kilowatt machine designed by Mr. Parshall.

Mr. Parshall has also published<sup>1</sup> very complete data of a slow-speed 550-kilowatt generator of the General Electric Company's design, which, though a rather heavy machine for its output, gave a very satisfactory performance from the point of view of cool and sparkless running. Fig. 76 shows the armature in section. Let us treat this machine as though we had to design it, adopting the order of procedure of p. 146. We are to produce a multipolar generator working at a terminal pressure of 500 volts (at no-load), and of 550 volts at the full-load of 1000 amperes, the engine speed being 90 revolutions per minute. Obviously it is to be over-compounded. The prescribed efficiency is 94 per cent. at full-load. As this is a slow-speed machine, the Steinmetz coefficient cannot be low; let us take it at 3·5. Then, by (2) on p. 140,  $550 \times 3 \cdot 5 = 1925 = d \times l$ , which we must presently fix. As the full-load is 1000 amperes, if we would not attempt to collect more than 200 amperes at any one row of brushes, we must have at least 10 poles and 10 rows of brushes (5 positive and 5 negative). With a 10-pole machine with steel poles, one would expect the armature diameter to be five or six times the length of the core-body. Then, since  $d \times l$  are to equal 1925, two approximate factors would be 100 and 19½. The dimensions actually used are  $d = 96$  and  $l = 20 \cdot 5$ ; so that the Steinmetz coefficient is actually 3·56. The peripheral speed is 2263 feet per minute, and the periphery 302 inches. This gives 30·2 inches for the pole-pitch at the armature face. Taking the

<sup>1</sup> *Street Railway Journal*, xvi. Oct. 1900; and *Electrician*, xlv. 670, Nov. 23, 1900.

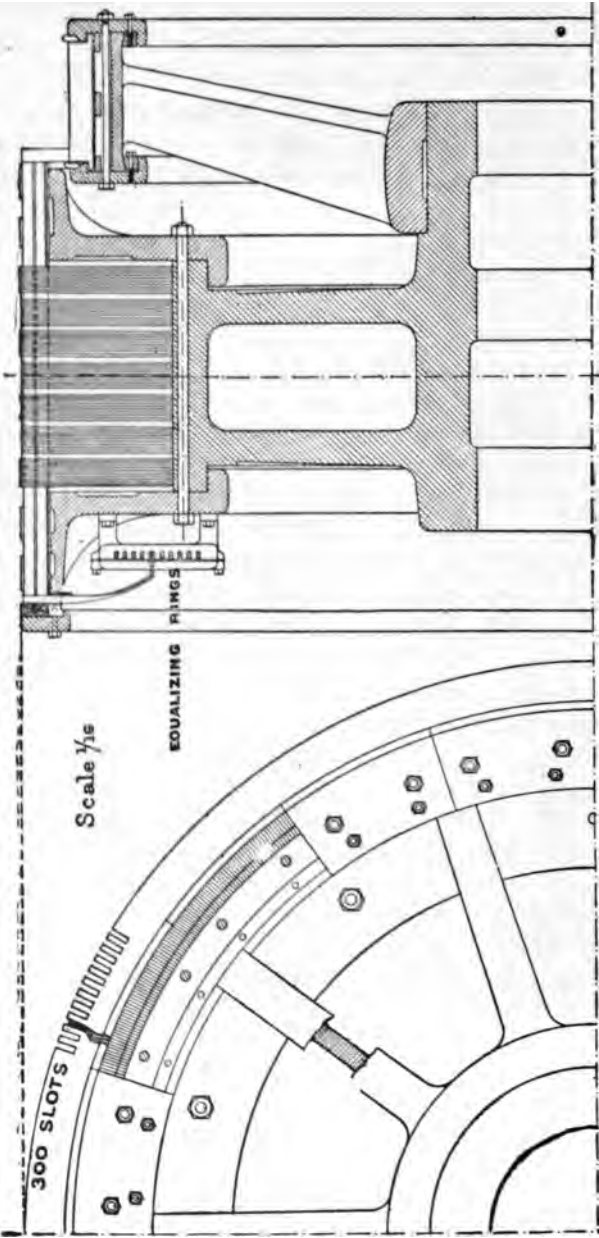


FIG. 76.—PARSHALL'S M P—10—550—90 TRACTION GENERATOR.

pole-arc at about 75 per cent. of the pole-pitch, or 22 inches, the area of pole-face (which is not quite rectangular, being bevelled at the outer corners to a polygonal form) will be about  $22 \times 20 = 440$  square inches. If we take 42,000 lines per square inch (at no-load) as a suitable pole-face density, that would make the flux from one pole to be  $N = 18,480,000$ , or 18.48 megalines. Now using the formula of (5), p. 148, since  $n$  (the revolutions per second) = 1.5 and  $E$ , the no-load voltage, is 500, we get for the trial value of  $Z$  the number of armature conductors:—

$$500 \times 10^8 \div (1.5 \times 18,480,000) = 1803.$$

The actual number in the machine is 1800 grouped in 300 slots, 6 conductors in each slot. Testing this by the rule that it is inadvisable to have more than 600 ampere-conductors per inch of periphery, we find 1800 conductors each carrying 100 amperes (since there are 10 paths for 1000 amperes) occupying 302 inches periphery, making 595 amperes per inch periphery, which is satisfactory. Further, as  $n = 1\frac{1}{2}$ , and there are 5 pairs of poles, the frequency of magnetization will be only  $7\frac{1}{2}$  cycles per second. There will be, of course, 900 segments in the commutator, and as these ought to be about 0.3 inch wide, the total periphery of the commutator ought to be about 270; it is in fact 272, the diameter being 86 inches, and the length of the segment about 9 inches. As the armature periphery is 302 inches, and there are 300 slots, the tooth-pitch will be 1.006 inch. The slot should be about half this; it is in fact 0.525 inch wide. As 6 conductors each carrying 100 amperes pass through the slot, and as the current-density in the copper will be about 1500 amperes per square inch, each conductor will need to be about 0.065 square inch in section, and the total section of copper in any one slot will be about 0.39 square inch. If

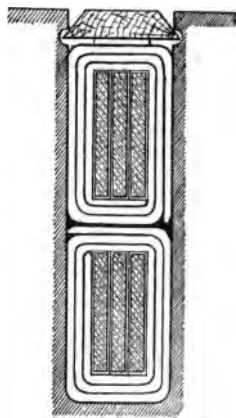


Fig 77.

SLOT OF PARSHALL'S  
550 KILOWATT MACHINE.

302 inches, and there are 300 slots, the tooth-pitch will be 1.006 inch. The slot should be about half this; it is in fact 0.525 inch wide. As 6 conductors each carrying 100 amperes pass through the slot, and as the current-density in the copper will be about 1500 amperes per square inch, each conductor will need to be about 0.065 square inch in section, and the total section of copper in any one slot will be about 0.39 square inch. If

the space-factor be assumed at about 0·4, this will show that the gross section of the slot must be nearly 1 square inch. As it is 0·525 inch wide it must therefore be nearly 2 inches deep. In fact, the slots are made exactly 2 inches deep, allowing for a wedge at the top. The copper conductor is 0·0641 square inch in section. The slots being 0·525 inch wide, the gap must not be much less. It was actually 0·375 inch. As this is to be an over-compounded machine there must be allowed a long pole-core, say, as a trial value, not less than 40 times the length of the gap, since the teeth also are long; or, say, 15 inches. The actual length was 18 inches. The principal data being thus accounted for, it will now suffice to add the following data as given by Mr. Parshall.

Nett iron length of armature core-body 14·9.

Internal diameter of armature-core 71.

Yoke (cast-steel), internal diameter 138·25.

Yoke, external diameter 149·6.

Yoke, diameter over ribs 157·5.

Yoke, length parallel to shaft 24.

Number of equalizing rings 10.

Number of equalizing points per ring 5.

Pitch of winding is over 29 teeth.

Armature-spider has 5 arms, with 15 dovetail notches to receive cores.

Style of winding, lap-wound, barrel-drum.

Average volts per segment of commutator 6·1.

Breadth of carbon-brushes 1 inch, or 3 segments.

Amperes per square inch brush-contact 40.

Shunt-wire makes 1154 turns per bobbin, and consists of 780 turns No. 9 B. and S., and 374 turns No. 10 B. and S.

Voltage-drop at full-load is as follows:—12·6 volts due to copper armature resistance (at 60° C.); 2·4 volts due to brush contacts; 0·6 due to resistance of the compound winding; or in total 19 volts. Hence, to give 550 volts at terminals, the internal electromotive-force generated at full-load must be 569 volts; which, assuming speed constant, means that the armature-flux at full-load must rise to 20,360,000 lines per pole. As-

suming a dispersion ratio of 1·125, this makes the values of the flux per pole in the pole-core 20·8 megalines at no-load (500 volts) and 23·6 megalines at full-load (550 volts).

The excitation is given by Mr. Parshall as follows :—

—	<b>B</b> No-Load.	<b>B</b> Full-Load.	Amp.-Turns, No-Load.	Amp.-Turns, Full Load.
Core-body . .	59,000	67,000	190	320
Teeth . . . .	108,000	119,000	340	900
Gap . . . .	42,500	48,500	5000	5700
Pole-core . . .	78,000	88,000	880	1530
Yoke . . . .	69,000	79,000	640	1000
	Totals . .		7050	9450

There are 180 conductors on the armature per pole, each at full-load carrying 100 amperes, making 18,000 armature ampere-conductors per pole, of which about 20 per cent., or 3600, are demagnetizing, and about 80 per cent., or 14,400, are cross-magnetizing. Total ampere-turns allowed for on each magnet pole at full-load at 550 volts 12,350.

The heat-waste in iron in the armature was estimated at 0·88 watts per pound; hence, as core weighs 12,600 lb., core-loss was 11,000 watts. Armature resistance, brush to brush, at 60° C., 0·0125 ohm. Hence  $C^2R$  loss for 1000 amperes was 12,500 watts. Total armature loss 23,500 watts. Peripheral radiating surface 12,000 square inches; therefore 1·97 watts per square inch. Observed rise of temperature after 8 hours' run at full-load, by thermometer 26° C., by resistance 38° C. Excitation losses: total  $C^2R$  loss per bobbin, at 60° C., 422 watts. External cylindrical radiating surface of 1 bobbin 1350 square inches; therefore 0·312 watts per square inch. Observed rise of temperature after 8 hours' run at full-load, by thermometer on surface of shunt coils 26° C., by resistance 45° C.  $C^2R$  loss at brush contacts 2400 watts; in commutator segments 400 watts. Friction loss at commutator 870 watts. Total watts lost in commutator 3670; radiating surface 2400

square inches; therefore 1.53 watts per square inch. Observed rise of temperature after 8 hours' full-load run, 22° C. This makes the total losses as follows:—armature 23,500, field-magnets 4220, commutator 3670; total 31,390 watts. Hence the efficiency (excluding friction at bearings) is  $550 \div 581 \cdot 39 = 0.945 = 94\frac{1}{2}$  per cent. Assuming a permissible temperature-rise (by thermometer) of 30° C., Parshall gives the following handy rules as to the requisite amounts of radiating surface:—

	Armature.	Field-Coils.	Commutator.
Radiating surface (sq. in.) necessary per kilowatt output of machine.	18.75	15	3.75

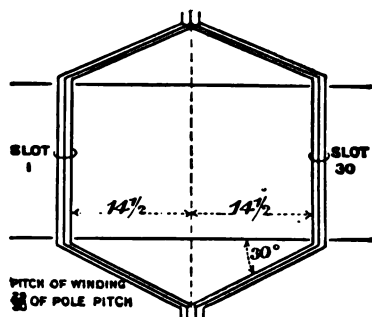


FIG. 78.—WINDING DIAGRAM OF PARSHALL'S 550 KILOWATT GENERATOR.

Constructional data of a larger General Electric Co.'s generator, M P 14—1000—100—575 volts—1740 amperes, are given by Hobart in an article in the *Elektrotechnische Zeitschrift*, xxii., p. 650, August, 1901, where they are compared with those of kindred machines of equal output by Rothert, and by Siemens and Halske (Vienna), see p. 232.

The firm of Kolben and Co., of Prag, has made itself known for the excellent types which Mr. Kolben has produced during recent years.

Fig. 79 depicts a small 4-pole machine of this firm, of 3 kilowatts' output. Though it has four poles, two of them only are wound, the other two being consequent poles at the sides of

the magnet-frame. Running at 1100 revolutions per minute, it generates 25 amperes at a pressure of 123 volts at the terminals. The magnet-frame and cores are of cast-steel; the bearing supports of cast-iron. The external diameter of the core-disks is 9·11 inches; the internal 4 inches. The length between core-heads is about  $4\frac{1}{2}$  inches. There are 6 slots, each

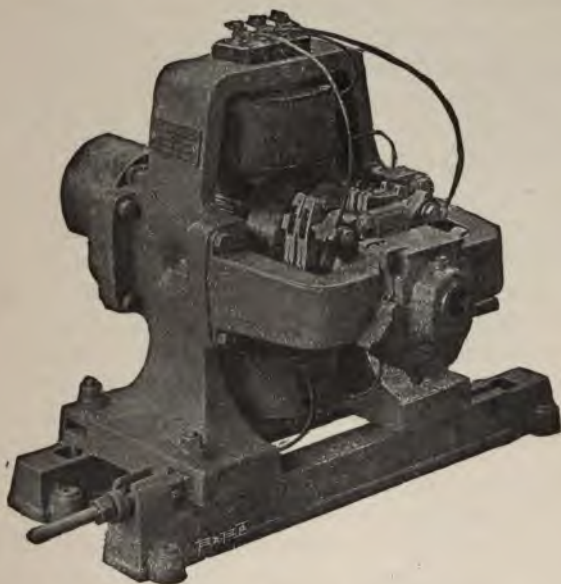


FIG. 79.—KOLBEN'S 4-POLE 3 KILOWATT DYNAMO.

0·788 inch deep and 0·167 inch wide. In each slot are 6 conductors, making 414 conductors in all, their diameter being 0·087 inch bare, covered to 0·110 inch. The gap-space is 0·118 inch. The commutator, of 69 segments is 4 inches in diameter, 2 inches long, and the mica insulation is 0·024 inch thick. There are two sets of carbon brushes with two brushes on each set, of a size allowing 1 square inch for 30 amperes. On each pole-core are wound a shunt coil of 2300 turns of a wire 0·040 inch diameter covered to 0·055 diameter, as shunt,

and 28 turns of a series winding 0·173 inches in diameter covered to 0·193 inch. The efficiency at full-load is 85 per cent.

Plates V., VI. and VII. show a Kolben traction generator, M P 10—250—125—550 volts—454 amperes.

The ten pole-cores are cast in one piece with the yoke, the whole being of cast-steel, with cast-steel pole-pieces screwed on. Plate VII. shows in detail the construction of the field-magnet bobbins and pole-pieces. The pole-pieces are skewed in order to ensure that the armature conductors in revolving shall come gradually into the field. This machine is compounded, each pole having  $5\frac{1}{2}$  turns of copper strip 5·32 inches wide and 0·059 inch in thickness wound outside the shunt-turns. The outside diameter of the yoke is 105 inches, the maximum radial thickness being 5·9 inches; the pole-cores are 13·97 inches in diameter. The field is bored to 67·25 inches, and the diameter of armature is 66·1 inches, the gap therefore being 0·575 inch long. The armature is wave-wound, the winding being a series-parallel, having four circuits in parallel, with ten sets of brushes. There are 437 slots, each 0·256 inch wide and 0·984 inch deep, and two conductors of 0·0652 square inch section, in each slot; there being thus in all 874 conductors. The space-factor, that is to say, the ratio of copper section to slot section, is 0·516.

The end connexions of the armature conductors are made by joining them together at separate insulated copper segments, held round the armature exactly like commutator segments, this construction being exceptionally good mechanically; the commutator risers are then simply sweated into cuts in these segments. The commutator has a diameter of 39·35 inches; there are 437 segments, or one segment per slot. Mica 0·036 inch thick is used for insulation between the segments. This generator is for direct coupling to engine, a flange being provided for the purpose on the end of the shaft. The armature spider is secured firmly to the shaft by means of steel rings pushed on to a shoulder on the spider while hot, the subsequent contraction effectually gripping the spider to the shaft.

The winding-scheme of this machine is specially considered and described on p. 102 above.

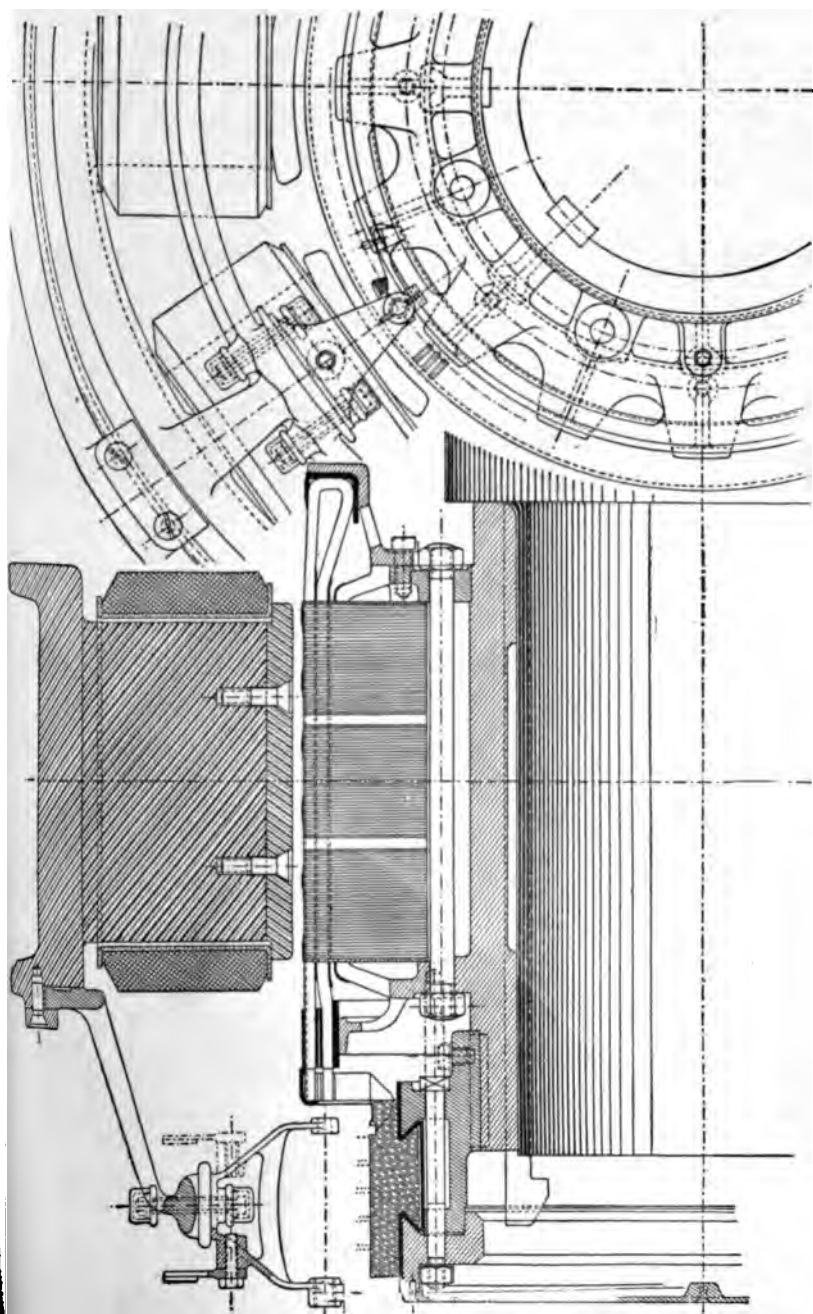


FIG. 80.—SLOW-SPEED EXCITER DYNAMO, MP X 10—38—75 (KOLBEN & CO.).

Fig. 80 illustrates a special type of generator, namely, a very slow-speed *exciter*, destined to be mounted on the end of the shaft of a large alternator, revolving at only 75 revolutions per minute. This entails peculiar variations in the construction.

The diameter of the core-disks is 33·8 inches; the length

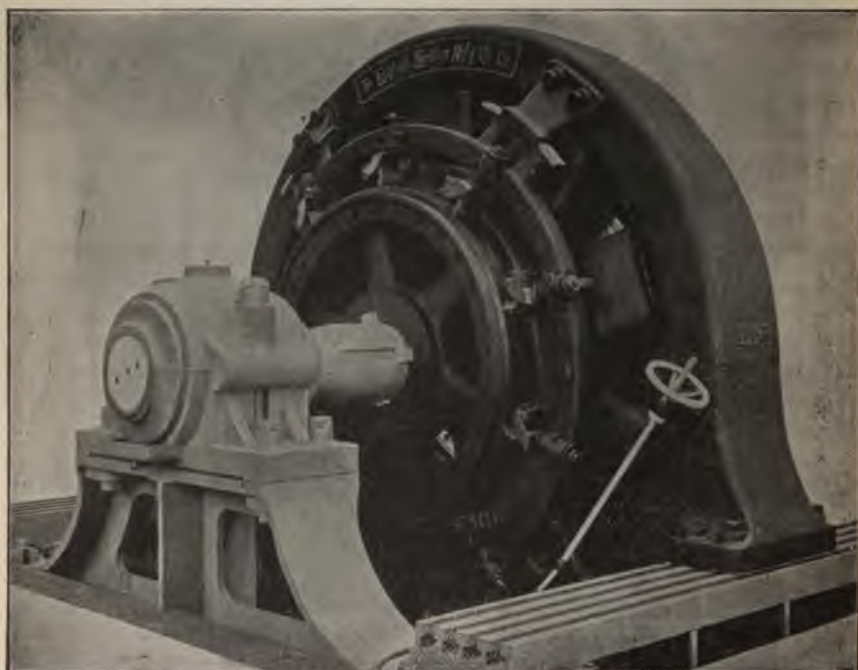


FIG. 81.—TRAMWAY GENERATOR OF THE ENGLISH ELECTRIC MANUFACTURING CO., PRESTON.

between core-heads 15·1 inches; and as the output is only 38 kilowatts the value of the Steinmetz coefficient reaches the abnormal value of 13·4. The commutator has a diameter only slightly less than that of the armature, the risers being necessarily very short. The machine is shunt-wound.

Several other machines of Messrs. Kolben & Co., are described in the Author's larger work.

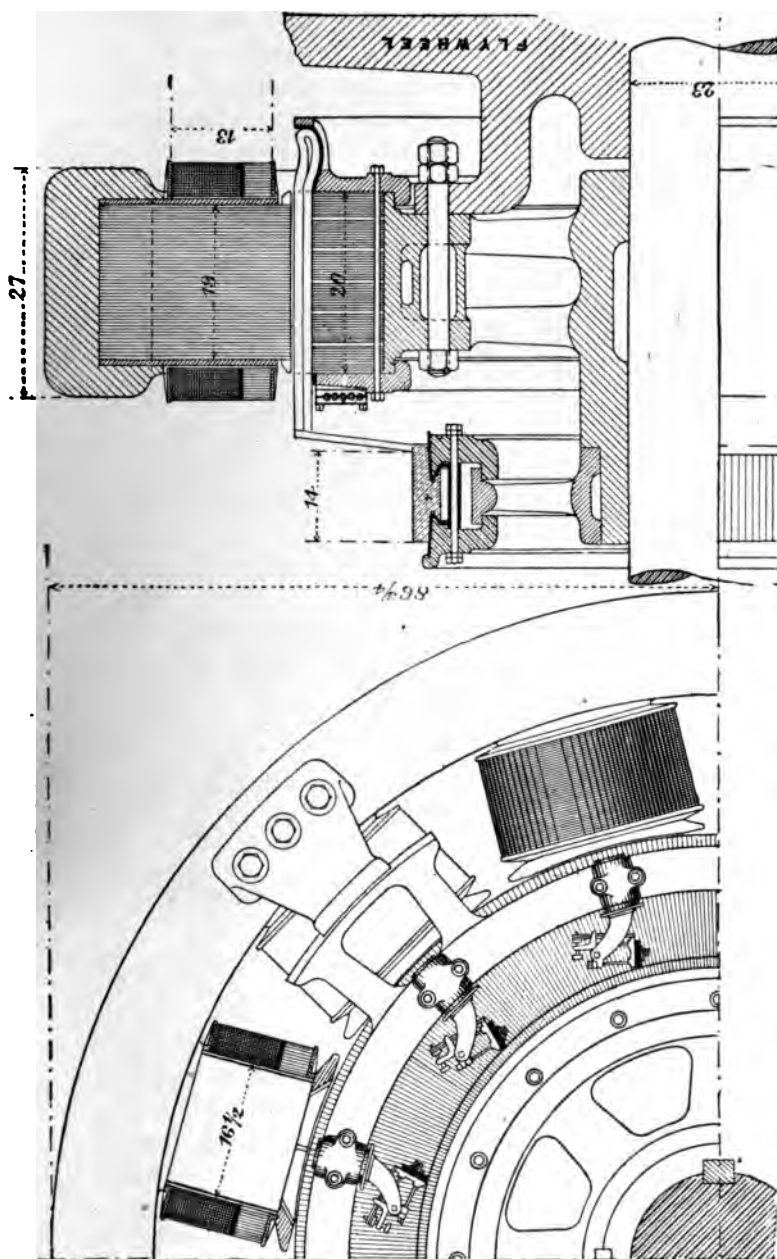


FIG. 82.—SECTION OF ENGLISH ELECTRIC MANUFACTURING CO.'S GENERATOR, MP 12-1100-100.

The English Electric Manufacturing Company (Dick, Kerr & Co.), of Preston, produce a standard type of generator designed by Mr. S. H. Short, depicted in Fig. 81. A sectional view of a 12-pole machine is given in Fig. 82. This is an 1100 kilowatt generator, running at 100 revolutions per minute. It has a heavy cast-iron yoke; the laminated pole-cores being cast in solidly, and a cast-iron pole-shoe attached by screw-bolts.



FIG. 83.—POLE-CORE STAMPINGS.

Fig. 83 shows the laminated pole-cores. The pole-shoes, as will be seen from Fig. 84, which gives a view of a magnet-frame, are in two halves, being secured in V-notches punched in the laminated pole-cores, the two halves being clamped together by bolts, a space being intentionally left between the two halves to assist in preventing distortion of the pole-face flux.

In order to secure a well-graded fringe at the pole tips they are notched, as is well shown in Fig. 84.

The construction of the shunt-bobbins is shown in Fig. 85. The bobbins have cast metal end plates cast in open design,

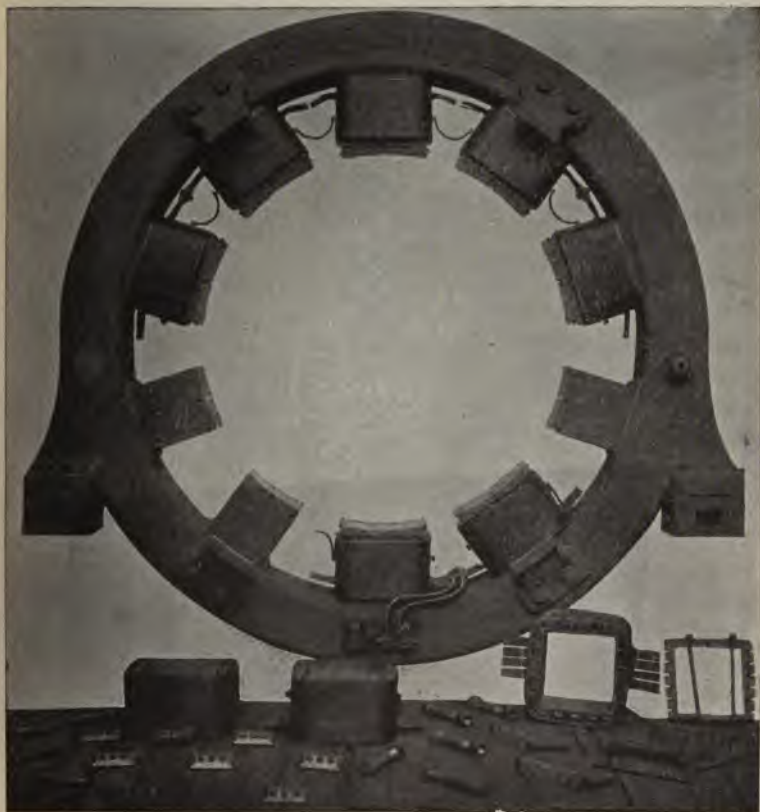


FIG. 84.—MAGNET-FRAME OF 10-POLE MACHINE.

to render the ventilation as good as possible. The shunt and compounding turns are wound side by side and not in superposed layers as is usual. The compounding turns are wound edgewise, of copper strip.

The armature is a simple lap-winding, each element being



FIG. 85.—FIELD-MAGNET BOBBINS.

a loop of strip copper in one piece. Fig. 87 shows the complete armature-core. Equalizing rings, or connexions short circuiting points of the winding at approximately equal potential



FIG. 86.—ARMATURE-CORE STAMPINGS.

are used to facilitate commutation; and their arrangement is plainly shown in the figure, between the commutator risers and end-plates of the armature.

Fig. 86 shows the core-plates of this machine, and the

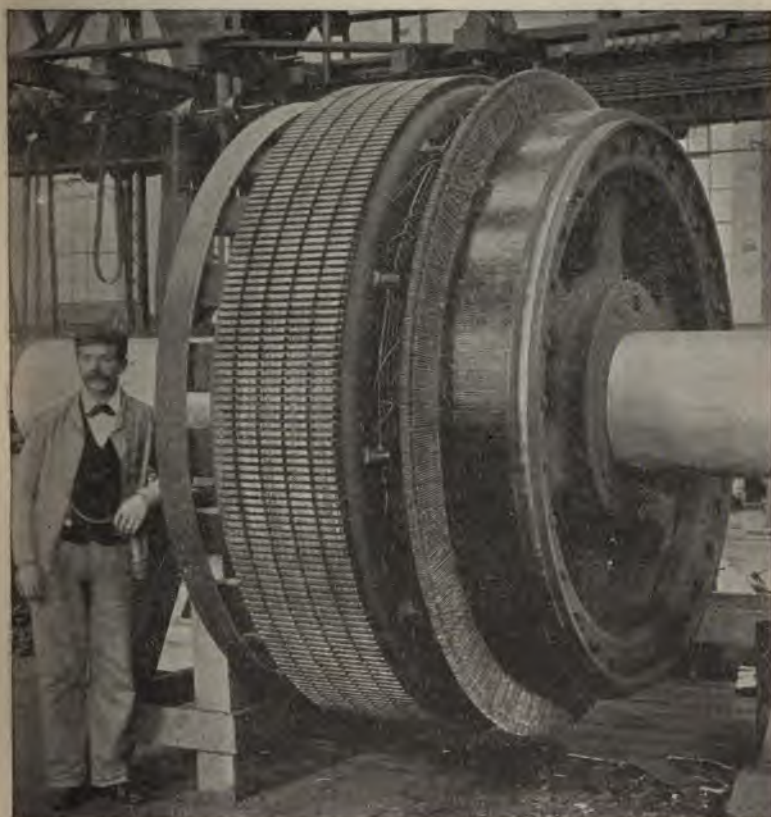


FIG. 87.—ARMATURE-CORE READY FOR WINDING.

process of manufacture, from the blank (numbered 1 in the figure) to the complete section (numbered 4). One of the core-plate separators to keep the laminations apart for the formation of ventilating ducts is also shown (numbered 3).

Fig. 88 shows the armature-spider ready machined. It has six arms, with dove-tail grooves for holding the core-plates. The commutator seating is plainly shown, as also the seatings and bolt-holes for securing the commutator to the spider.

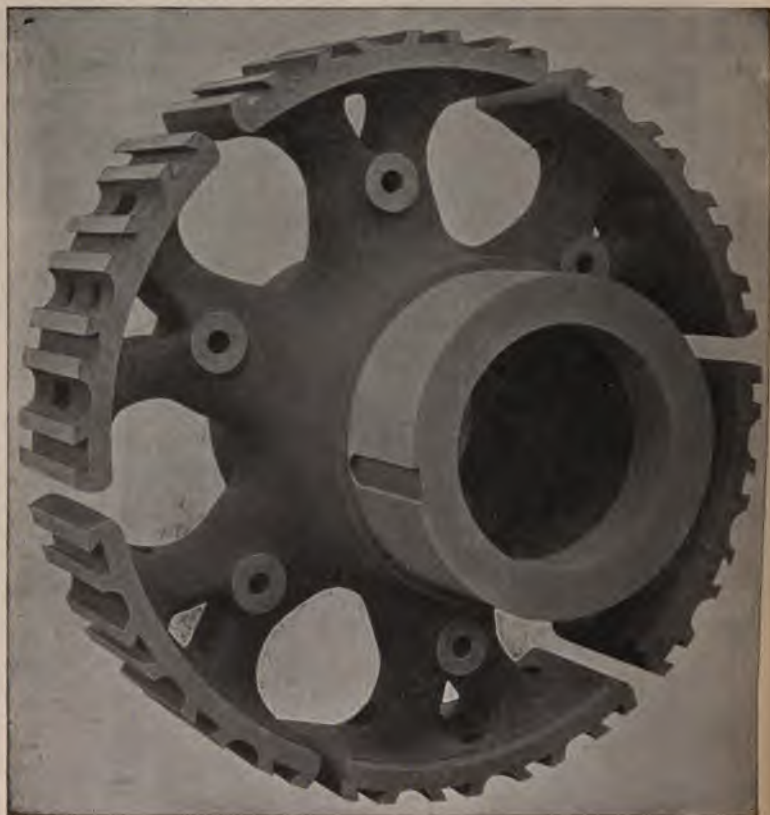


FIG. 88.—ARMATURE-SPIDER.

Fig. 89 shows the brush gear; the brush-rocker is carried on a massive cast-iron ring, which is bracketed out from the yoke, as is shown in Fig. 81, a worm-wheel being used to shift the rocker for adjustment of the brushes.

The firm known as La Compagnie de l'Industrie Electrique, of Geneva, has done much continuous current work for lighting and power, as well as for electrolytic purposes. Figs. 90 and 91 depict one of their electrolytic generators designed by M. Thury, viz. :—

$$M P 12-832-\frac{90}{120}-208_v-4000_A.$$

This machine, which is at work at Chévres is of the vertical type, and is driven by a 1200 horse-power turbine at a speed varying from 90 to 120 revolutions per minute. The output



FIG. 89.—BRUSH-GEAR.

is 4000 amperes at 208 volts. This generator has the yoke and pole-pieces of the pattern peculiar to the designs of M. Thury. Each shunt-bobbin is wound with 448 turns of wire of 33 square millimetres section, and the 12 coils are connected as usual in series. The armature has 468 slots, each slot containing one conductor of 120 square millimetres section; the end connections being made by butterfly connectors of 140 square millimetres' section.

The commutator is 1000 millimetres in diameter, has 234 segments, with two working lengths of 390 millimetres, a steel ring being shrunk on the outside surface of the commutator,

at its middle point, to guard against any excessive centrifugal strain on the heavy commutator segments; this ring is, of course, adequately insulated from the surface of the commu-

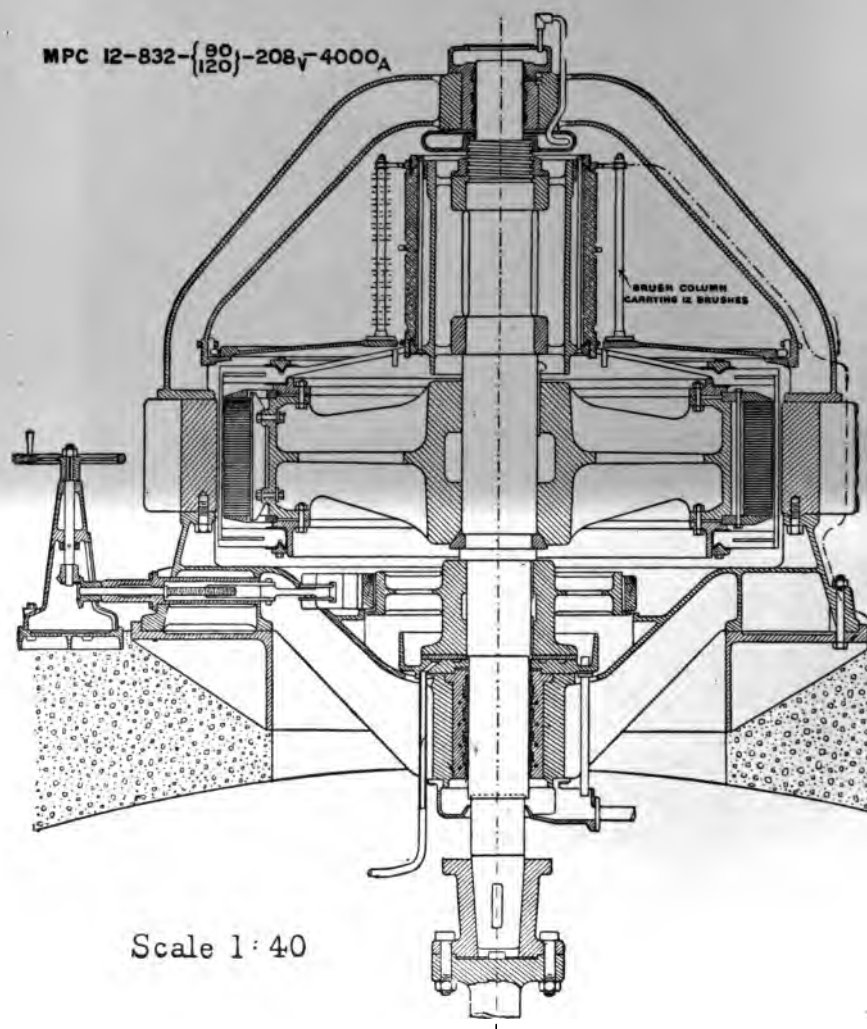


FIG. 90.—THURY'S ELECTROLYTIC GENERATOR: SECTION.

tator. The 4000 ampere current is collected by twelve sets of brushes, each set consisting of 24 carbon brushes, the 24 brushes being again subdivided into two sets of twelve brushes. For other Thury machines see the Author's larger work.

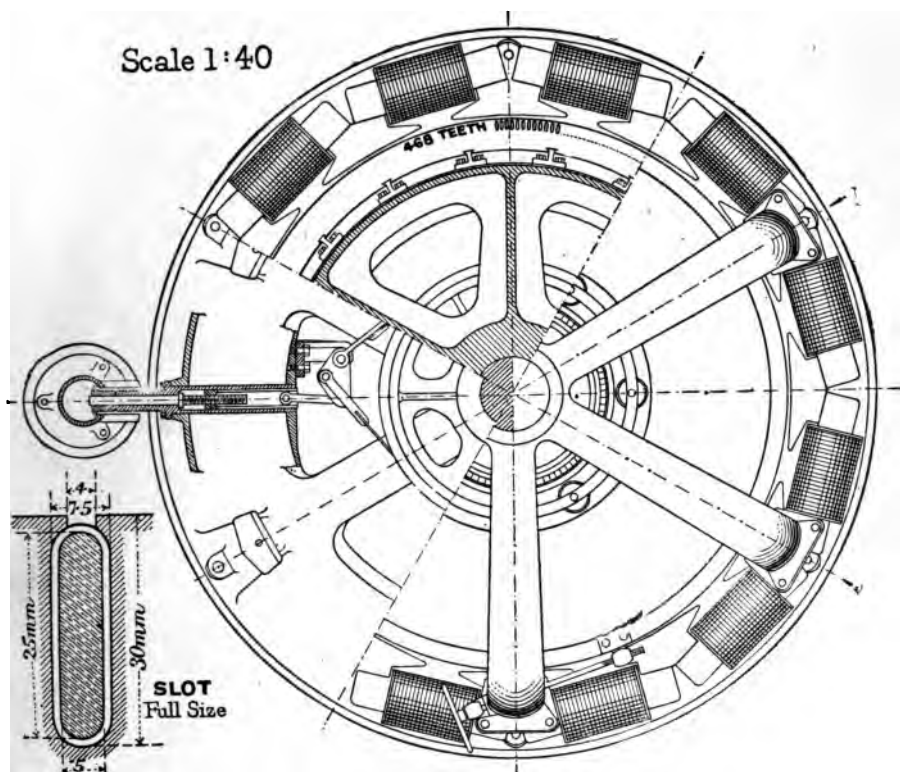


FIG. 91.—THURY'S ELECTROLYTIC GENERATOR: PLAN.

A generator by the International Electrical Engineering Company, of London, is shown in Plate VIII., M P 8—450—250—500 volts—900 amperes, having cast-steel poles cast in one piece with the yoke. It has laminated pole-shoes bolted on after the shunt-bobbins are placed in position. The outside

diameter of yoke is 91 inches, radial length of pole-core 15 inches, and the bore of field is 49·7 inches, and the armature being 49 inches in diameter, the length of air-gap is about 0·35 inch. The total flux from one pole at no-load is 20·15 megalines, and as the area of pole face is about 280 square inches, the pole-face density is about 73,000 lines at no-load, which is rather high. In this machine in fact both the magnetic fluxes and current densities are pushed as high as possible, but a fairly high armature surface speed, combined with careful design as regards ventilating capabilities, enables this to be done, without excessive heating. There are 1350 turns on each field-bobbin, and the poles being circular the mean length of one turn is 58·6 inches; the shunt-winding space is 11·5 inches in length and the wire is wound to a depth of 2·75 inches.

There are 200 slots and 800 conductors 0·118 inch by 0·443 inch, and consequently there are four conductors per slot, the slots being 0·394 inch wide and 1·18 inch deep. The winding has eight parallel circuits and eight sets of brushes. The armature has three ventilating ducts and the stampings are held by two substantial end castings bolted on to a spider of simple design. The commutator is bracketed out from the main armature-spider, being secured by screws; the diameter of the commutator is 33 inches and the segments are  $12\frac{1}{2}$  inches over all.

Mr. H. M. Hobart, who has written on dynamo construction in conjunction with Mr. Parshall, has contributed to the subject of dynamo design a paper<sup>1</sup> in which he gives particulars of a large number of machines of his own designs. Amongst these is noticeable a large generator, M P 22—1600—85—550 volts—2900 amperes, which has the high peripheral speed of 4000 feet per minute and the remarkably low Steinmetz coefficient of 1·44, showing great economy of material. The chief data of this machine are as follows.

<sup>1</sup> *Journ. Inst. Elec. Eng.*, vol. xxxi. p. 170, 1901. See also some articles by Hobart in *Electrical Review*, vol. 1. p. 329, *et seq.* February and March, 1902.

**Armature:—**

Core disks, external diameter (inches)	177
“ internal	148
Number of slots	440
Depth of slot (inch)	1·34
Width “	0·55
Pitch of slot at armature face (inch)	1·26
Depth of iron in core, under teeth (inches)	13·36
Gross length of core (inches)	13
Iron “ “	8·6
Diameter of finished armature (inches)	177
Number of conductors	2640
Arrangement	6 in a slot
Style of winding	parallel (lap)
Dimensions of each conductor, bare (inches)	$0·53 \times 0·118$
Section of each conductor, (square inch)	0·0625
Minimum width of tooth	0·735
Number of ventilating ducts	7

**Field-Magnets:—**

Diameter of bore (inches)	177·79
Pole arc ratio (per cent.)	72
Diameter of magnet core	15
Length of “	19·18
External diameter of yoke (inches)	254
Gap	0·394
Flux in magnet cores (megelines)	17
Flux-density in pole-cores (steel)	97,000
“ in gap at pole face	64,000
“ in yoke (steel)	35,000
“ in teeth (apparent)	148,000
“ in core body	63,000

**Commutator:—**

Diameter (inches)	138
Number of segments	1320
Active length (inches)	9·6

**Other data are as follows:—**

Current density in armature conductor	2128
Space-factor of slot	0·51
Average volts per segment of commutator	9·2
Current density in brush face	32·2
Armature ampere-turns per pole	7900
Amperes in one conductor	132
Ampere-conductors per inch peripheral	627
Ampere-turns per pole at no-load	13,000
“ “ “ “	16,000

The losses are as follows at full load:—

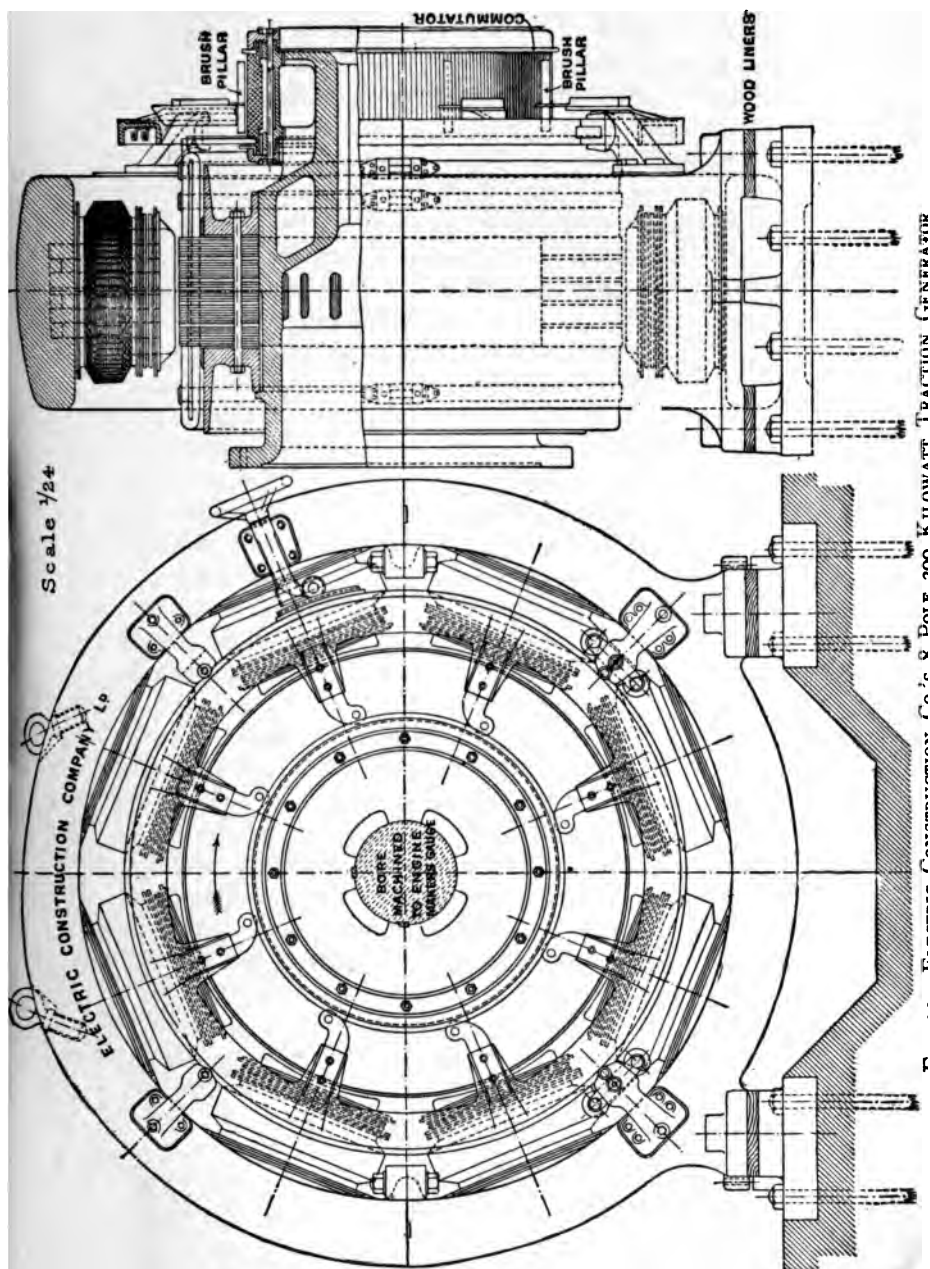
Armature iron loss (watts)	32,000
" copper loss	24,400
Commutator resistance loss	5,800
" friction loss	5,300
" stray losses	300
Excitation, shunt	13,000
" " rheostat	2,000
" series	3,000
" " diverting shunt (see p. 131)	1,000
<hr/>	
Total	86,800
Total constant losses	52,600
" variable losses	34,200
Commercial efficiency, full-load (per cent.)	94.9
" " half-load	92.8
" " quarter-load	88.1

The number of watts wasted per square inch of peripheral surface with a temperature-rise of 60° C. was 3.9 in the armature, 2.4 in the commutator, and 0.58 in the magnet-coils.

The core stampings weighed 7.7 tons, the armature copper 1.1 tons, commutator segments 1.7 tons, the magnet copper 2.7 tons, the pole-cores 10 tons, total magnet yoke (with feet) 33 tons.

Another machine, M P 16—1000—90—500 volts—2000 amperes, described in the same paper by Mr. Hobart, and constructed by the Union Elektrizitäts Gesellschaft, for Sheffield, is fully described in the *Elektrotechnische Zeitschrift* for Jan. 16, 1902, vol. xxiii., p. 45.

Fig. 92 gives a view of a machine M P 8—300—150— $\frac{500}{550}$  volts—600 amperes, by the Electric Construction Company of Wolverhampton. The yoke is of soft cast-iron, and the pole-cores of sheet iron stampings cast in; with soft iron forgings for pole-shoes screwed on. The armature-core is built up of charcoal iron stampings of 11 inches radial depth, assembled to a gross length of 15 inches including four air-ducts. It is clamped between cast end-plates, which have brackets to carry the barrel-windings. The armature and commutator are



mounted on a cast-iron spider keyed at the commutator end to the shaft, but expanded at the other end into a wide driving-flange that is bolted to the boss of the fly-wheel. On the inner part of the spider are cast oblique webs to serve as fans. The armature-winding consists of 1536 conductors of strip of a sectional area stated to be 0.0636 square inch. The commutator, which is 42 inches in diameter, with a working face  $11\frac{1}{2}$  inches long, has 768 segments. Each section of the winding consists of a single jointless loop bent edge-on at the end away from the commutator, and former-shaped. The external diameter of the armature is 62 inches. The slots have straight sides, and are lined with separate insulation. The insulation resistance is stated at 100 megohms, and the temperature rise after 8 hours' full-load run is stated not to exceed  $28^{\circ}$  C. The conductors are secured in the slots by wedges of hard wood, and by binding wires over the projecting ends. The rocker-ring runs on rollers bracketed out from the yoke, with an adjusting worm-wheel gear. The shunt-current at normal full-load is 8.3 amperes; the shunt-winding being former-wound with coned ends. The machine is over-compounded by 10 per cent., the full-load voltage rising to 550 volts. The series-winding is also former-wound, of rectangular strip, wound edge-on, of two flat spirals united together at the inner periphery, thus bringing both free ends to the surface. At full-load the series-winding takes up about 1.2 kilowatts, being therefore about 0.033 ohm in resistance.

A large traction generator constructed by Siemens and Halske, of Vienna,<sup>1</sup> was shown by this firm at the Paris Exhibition of 1900. Its type is M P 14—1000—95—550 volts, thus giving 1820 amperes at full-load. The armature has a diameter of 98.5 inches; the length between core-heads is 21.3 inches. There are five ventilating ducts, each about 0.4 inch wide. There are 1144 conductors, each 0.157 inch  $\times$  0.71 inch, and four of these conductors are placed in each slot, there being therefore 286 slots, the size of the slots being 0.51 inch wide

<sup>1</sup> *Zeitschrift für Electrotechnik*, vol. xviii. p. 551, 1900.

by 1.97 inches in depth. The winding is series-parallel with 10 circuits. The commutator is 82 inches in diameter, with 572 segments, mica 0.031 inch thick being used for insulation between the segments. The minimum length of air-gap is 0.35 inch, and the maximum length 0.47 inch, the average flux-density in the gap being 58,000 lines. The yoke is of cast-steel, the overall dimensions of the machine being 156 inches or 13 feet.

The fourteen field-bobbins have each 770 turns of wire, the ampere-turns at full-load coming out to about 18,500, the excitation required for this being about 13 kilowatts, or 1.3 per cent. of the full-load output of the machine. There are 14 sets of brushes.

The temperature-rise after 24 hours' full-load run is 30° C.

The total weight of the machine is just over 100,000 lb., or 44½ tons.

*Summary.*—The machines which have now been described are summarized in the following Table in order to afford a view of the several values of the more important coefficients adopted in their design. The coefficients  $\alpha$  and  $\beta$  in the later columns are explained on p. 158 above, and signify respectively the gross values of the average current-density and of the average magnetic density in the active belt at normal full-load. The values in the last column of kilowatts of output per cubic inch of the active belt are, like the preceding, deduced from the normal full-load output for which the machines are rated. All makers do not, it is well known, adopt the same basis for the rating of their machines, for some allow a higher temperature-rise than others. It is quite impossible to reduce the values to a common basis in this respect. Nevertheless the values given are not altogether unfair as a means of comparison. If in any machine the peripheral speed is high, there is necessarily a higher specific utilization of material. And if in any machine in which this is high the  $\alpha$  and  $\beta$  densities are also high, the output per cubic inch of active belt, and therefore the output in proportion to weight and cost, will also be high. The 8-pole machine of the International Electrical Engineering

TABLE OF SPECIFIC UTILIZATION COEFFICIENTS AND OTHER FEATURES OF DESIGN IN CONTINUOUS CURRENT GENERATORS.

Maker or Designer.	Specification.						Steinmetz Coefficient $\sigma$	Current in one conductor $C_1$ .	Ampere conductors per inch.	Peripheral speed ft. per min.	$\frac{C \times Z}{e \times \pi d^2 \times a} = \alpha$	$\frac{\rho N}{\pi d \times l} = \beta$	Watts per cub. in. of active belt.
	Type.	Poles.	Kw.	R. P. M.	V. lts.	Amp.							
Brown Boveri & Co.	MP	8	194	350	490	396	2.47	49.5	575	3860	302	27400	62.5
Electric Construction Co.	MP	8	300	150	500	600	3.1	75	592	2430	246	39500	43
English Elec. Manfg. Co.	MP	12	1100	100	550	2000	1.96	166	610	2830	390	51400	103
General Elec. Co.	MP	10	550	90	550	1000	3.95	100	595	2760	297	32700	44.4
Hobart . . .	MP	22	1600	85	550	2900	1.44	132	627	4000	467	47000	163
International Elec. Eng. Co.	MP	8	450	250	500	900	1.96	112	585	3200	496	47500	140
Kolben & Co. .	MP	4	70	750	260	270	4.6	135	408	4600	399	18200	67.4
Kolben & Co. .	MP	10	250	125	550	455	4.35	114	477	2200	485	35600	74
Oerlikon Co. . .	MP	4	265	370	450	510	2.9	255	430	3860	365	29000	92
	MP	4	265	370	550	360	2.9	180	348	3860	340	33800	106
Oerlikon Co. . .	MP	10	165	110	280	590	4.48	59	660	2160	440	25000	46
Oerlikon Co. . .	MP	12	330	100	550	600	4.2	100	429	2640	363	37400	63
Scott & Mountain	MP	6	150	450	250	600	2.42	100	473	3040	296	37800	80
Siemens & Halske	MP	14	1000	95	550	1820	2.07	182	672	2460	310	50500	70
Walker Co. .	MP	10	440	85	550	800	3.6	80	585	2000	336	40500	44
EXCEPTIONAL DESIGNS.													
Brown Boveri & Co. (High Voltage)	MP	4	20	700	1000	20	7.35	10	300	2740	273	25900	39
Kolben & Co. (Exciter)	MPX	10	38	75	150	254	13.4	127	516	660	437	34700	20
Oerlikon Co. (Electrolytic)	MPC	32	560	55	80	7000	5.1	228	447	2540	505	28600	71
Oerlikon Co. (Electrolytic)	MPC	6	285	450	190	1500	2.18	250	835	4200	580	24070	117
Thury (Electrolytic)	MPC	12	832	120	208	4000	3.15	333	435	3580	368	29100	78

Company, and the 22-pole machine designed by Mr. Hobart, are cases in point. The high specific values attained in these machines unquestionably indicate the way to future economy in design. Everything points to the adoption of high-speed steam-turbines for all steam-driven dynamos of large power. With such speeds as these machines entail, very high surface-speeds will be reached; and design must be modified to meet these conditions. Greater axial lengths and relatively smaller diameters of armature will be a necessity; while with the high commutator speeds carbon brushes cannot be used. Both these influences will render greater the difficulties of sparkless commutation, and make more needful than ever the most careful attention to the question of saturation of teeth and of pole-pieces, and the combatting of armature distortion. But they will also bring about a higher specific utilization of material.

With the introduction of large gas-engines and the commercial production of cheap gaseous fuel, it would seem likely that for all generators exceeding 1000 kilowatts, gas-engines will be employed rather than steam-engines, in case water power is not available. This development will again influence dynamo-design: and as is very evident, the dynamos of largest output are precisely those in which the best ventilation can be attained, and in which the highest specific utilization of electric and magnetic materials is possible.



# APPENDIX I.

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Gauge Number S. W. G.	Size Inch	Ohms per Cubic Inch at 15° C. (No Bed- ding).	Space Factor (No Bed- ding).	Feet per Ohm at 15° C.	Lbs per Ohm (bare) at 15° C.	Ohms per Lb. (bare) at 15° C.	Gauge Num- ber S. W. G.
0000	000	.000029350	.7401	15715	7611	.00013139	0000
000	000	.000039066	.7369	13592	5693	.00017566	000
00	000	.000050797	.7339	11895	4361	.00022933	00
0	000	.000067262	.7302	10310	3276	.00030523	0
1	000	.000091203	.7260	8839	2408	.00041526	1
2	001	.00012912	.7211	7481	1725	.00057980	2
3	001	.00018016	.7155	6236	1199	.00083424	3
4	001	.00024877	.7098	5286	861.2	.0011612	4
5	001	.00035357	.7032	4413	778.6	.0016660	5
6	002	.00052063	.6944	3614	402.5	.0024841	6
7	002	.00072901	.6875	3039	284.6	.0035137	7
8	003	.00105301	.6794	2513	194.7	.0051355	8
9	003	.0015747	.6697	2038	128.1	.0078090	9
10	004	.0024948	.6528	1601	78.97	.015225	10
11	005	.0036393	.6408	1318	53.33	.018750	11
12	007	.0054736	.6316	1063	34.82	.028717	12
13	009	.0086771	.6139	831.4	21.300	.046949	13
14	012	.014719	.5939	628.6	12.178	.082115	14
15	015	.021778	.5766	509.2	7.9966	.12515	15
16	019	.033707	.5571	402.3	4.9884	.20047	16
17	025	.056592	.5483	308.0	2.9240	.34200	17
18	034	.099473	.5191	226.2	1.5773	.63399	18
19	049	.19171	.4830	157.1	.76037	1.3152	19
20	061	.29070	.4811	127.3	.49951	2.0020	20
21	077	.44140	.4559	100.6	.31173	3.2079	21
22	101	.70395	.4262	77.00	.18273	5.4727	22
23	138	1.1971	.3913	56.59	.098651	10.137	23
24	164	1.6087	.3712	47.43	.069481	14.392	24

## STANDARD Wine GALLONS 22.5

[illegible]

app 2 running

# APPENDIX III.

## SCHEDULE FOR CONTINUOUS CURRENT DYNAMO DESIGN.

Type of Machine \_\_\_\_\_; \_\_\_\_\_ Poles ; \_\_\_\_\_ Kw. ; \_\_\_\_\_ Revs. p. min. ;  
\_\_\_\_\_ Volts ; \_\_\_\_\_ Amperes.

Design calculated by \_\_\_\_\_

Machine constructed by \_\_\_\_\_

In operation at \_\_\_\_\_

Type \_\_\_\_\_

Weight complete \_\_\_\_\_

Voltage, No Load \_\_\_\_\_ Full Load \_\_\_\_\_

Over Compounding \_\_\_\_\_ Volts, \_\_\_\_\_ %

## COMMERCIAL TEST.

Load.	Revs. per minute.	Volts.	Current.		Output Kw.	Losses—Watts.					Effi- ciency.
			Arm.	Shunt.		Arm. Cop- per.	Arm. Iron.	Exci- tation	Friction.	Total.	
No Load ...											
1/4 Load ...											
1/2 Load ...											
3/4 Load ...											
Full Load...											
1 1/4 Load ...											

Test made after \_\_\_\_\_ hours continuous run ; Armature

Current \_\_\_\_\_ amps. ; Shunt current \_\_\_\_\_ amps. ;

E.M.F. \_\_\_\_\_ volts. Resistance in shunt \_\_\_\_\_ ohms.

Measured Resistance of Shunt Winding : cold ( \_\_\_\_\_ °C.) \_\_\_\_\_ ohms. ;

hot ( \_\_\_\_\_ °C.) \_\_\_\_\_ ohms.

Remarks : \_\_\_\_\_

Date of test \_\_\_\_\_ Test made by \_\_\_\_\_

## DIMENSIONS.

### ARMATURE.

diameter at face  
periphery  
pole pitch at armature face  
length between core heads  
diameter  $\times$  by core length + kilowatts  
thickness of core sheets  
number of ventilating ducts  
width of each duct  
effective length of core  
radial depth core body  
internal diameter core  
number of slots  
depth of slot  
width " "  
" " at armature face  
minimum width of tooth  
width of tooth at armature face  
total number of face conductors  
number of circuits  
style of winding  
number of conductors in series between  
+ and —  
size or section of conductor (bare)  
size or section of conductor insulated  
mean length of conductor per turn  
pitch of winding (front and back)  
" " number of teeth  
arrangement of conductors in slot  
copper section + slot section (space  
factor)  
length of active conductor per volt  
total insulation between conductor and  
core

### GAP.

length at centre from iron to iron  
diameter of bore of field

### POLE PIECE.

length parallel to shaft  
length of pole arc  
average pole arc + pitch

### MAGNET CORE.

length radially  
length parallel to shaft  
width or diameter

### BOBBIN.

length over all  
thickness of insulation on flanges  
" " " body  
length of shunt winding space, excluding  
insulation  
size of shunt wire  
mean length of one turn  
compound conductor, size or section of

### YOKE.

outside diameter  
inside diameter  
thickness  
length parallel to shaft

### COMMUTATOR.

diameter  
length of segment over all  
area of cylindrical surface  
active length of segment  
number of segments  
width of segments  
useful depth of segment  
thickness of insulation between segments  
peripheral speed, ft. per min.

### COMMUTATOR BRUSHES.

number of sets  
number in one set  
length side by side  
width (peripheral) of brush in inches  
" " " in segments  
size of contact face  
total area of contact, one polarity

## ELECTRICAL.

### ARMATURE.

E.M.F. per circuit, no load  
" " full load  
type of winding  
number of turns per segment  
winding formula  
amperes per circuit of winding  
amperes per square inch in conductor  
C R drop (lost volts) in armature  
ohms brush to brush (at 60° C.)  
amperes per square inch of active peripheral belt

### COMMUTATOR.

average volts between bars  
reversal density + pole face density  
amperes per square inch of brush contact  
C R drop due to brush contact

### FIELD COILS.

type  
number of turns in series per bobbin  
number of bobbins in series  
mean length of one turn  
total resistance (at 60° C.)  
amperes, full load  
amperes, no load (shunt excitation)  
amperes, per square inch, full load  
rheostat resistance  
C R drop (lost volts) in rheostat

### COMPOUND WINDING.

arrangement of  
number of turns in series per bobbin  
mean length of one turn  
total resistance (at 60° C.)  
amperes full load  
amperes per square inch, full load

## REACTIONS.

### ARMATURE.

ampere conductors, per pole  
" " beneath pole  
" " between poles  
" " per inch periphery,  
full load  
" turns, gap and teeth + beneath  
pole  
density in gap under backward pole-horn  
at  $\frac{1}{2}$  load

### FIELD.

ampere turns, no load, no load volts  
" " full  
% added for armature reaction  
total ampere turns, full load  
ampere turns shunt coil, full load  
" " compound coil, full load  
" " total  
inherent regulation %

# SCHEDULE OF CALCULATIONS FOR WINDING OF FIELD MAGNETS.

Flux at no-load.....lines; Flux at full-load.....lines. Co-efficient of allowance for dispersion.....

	Flux from one pole (megallines).	Sectional Area.	Flux Density.	Mean magnetic length.	Ampere-turns per unit length (from curve).	Ampere-turns needed.
At No-Load.						
Armature body						
Teeth . . .						
Gap . . .						
Pole Core . . .						
Yoke . . .						

**GAP CO-EFFICIENTS.**  
**N.B.**—In calculating air-gaps the number of ampere-turns needed, per inch length across the flux-density  $I$  expressed in lines per square inch; or the number of ampere-turns needed, per centimetre length of gap, is obtained by multiplying by 0.796 the flux-density if expressed in lines per square centimetre.

**COMPENSATING REACTION.**  
 The number of demagnetizing ampere-turns per pole may be approximately calculated by reckoning the number of conductors in the region between two adjacent pole-horns and multiplying this number by the number of ampere-turns carried by each conductor.

= Ampere-turns of shunt-winding. Shunt current, taken at \_\_\_\_\_ per cent. of full load current, \_\_\_\_\_ amperes; hence Number of Shunt-turns per pole = \_\_\_\_\_.

= Ampere-turns to be provided by compound winding. Full-load current is \_\_\_\_\_ amperes; hence Number of Series turns per pole = \_\_\_\_\_.

**REMARKS.**

Total ampere-turns needed at no-load =

At Full-Load.						
Armature body						
Teeth . . .						
Gap . . .						
Pole Core . . .						
Yoke . . .						

Total ampere-turns needed at full load . . . =

Add ampere-turns needed to compensate reaction =

Deduct ampere-turns at no-load . . . =

Difference . . . =

## CALCULATION OF SHUNT BOBBIN.

Assuming suitable current density, ..... amperes per square inch of copper, the appropriate wire will be No. .... S.W.G. This wire has ..... diameter bare, or ..... diameter covered. The number of shunt-turns being ..... these will occupy ..... square inches of winding space on the bobbins. The available length of winding space on the bobbins being ..... inches, the depth occupied will therefore be ..... inches. Minimum circumference of winding ..... inches; maximum circumference is ..... inches; hence mean length of one turn is ..... inches = ..... feet. Resistance of one bobbin ..... ohms (at 60° C.). Watts lost in one bobbin ..... watts. Weight of ..... feet, in lbs ..... pounds. Assuming total watts lost in all shunt coils to be 0.75 per cent. of total out-put (kilowatts) of machine, this limits loss per bobbin to ..... watts. Taking this value, weight of copper per bobbin may be found by following formula—

$$\text{Pounds of copper per bobbin} = 31 \times (\text{ampere-turns} \times \text{mean length of one turn in feet})^2 \div \text{watts per bobbin at } 20^{\circ} \text{C} \times 10^6$$

Bobbins being ..... inches long, with ..... inches external diameter the cooling surface is ..... square inches; watts per square inch .....; hence probable temperature rise ..... deg. C. **N.B.**—Total radiating surface of all the bobbins ought to be about 15 times the total kilowatts of out-put. Probable temperature rise 75° C. per watt per square inch.

## CALCULATION OF SERIES WINDING.

Assuming current density ..... amperes per square inch of copper, the needful cross-section will be ..... square inches, and may be provided by strip copper of thickness ..... inch (= No. .... S.W.G.) and ..... inches broad. Mean length of one turn ..... inches; total length of strip required ..... inches = ..... feet for one pole, or ..... feet in total.

## TEMPERATURE TEST.

CONDITIONS OF TEST.					DEGREES RISE—CENTIGRADE.								
Duration.	Volts.	Armature Current.	Shunt Current.	Temp. Room.	Armature		Shunt.		Series.		Comm'r.	Bearings.	Frame.
					Ther.	Res.	Ther.	Res.	Ther.	Res.			
After    hours run													
"            "													
"            "													
"            "													

*Remarks* \_\_\_\_\_

*Date of test* \_\_\_\_\_ *Test made by* \_\_\_\_\_

## WEIGHTS AND COSTS.

Machine Parts.	Material.	Weight.	COST OF FINISHED PRODUCT.			
			Per Pound.	Total.	Per Kw.	Per 100 Revs.
Yoke    ...    ...						
Poles    ...    ...						
Armature Core    ...						
Armature Copper ...						
Commutator    ...						
Shunt Coil    ...    ...						
Series Coil    ...    ...						
Armature Spider. ...						
Armature Shaft    ...						
Brush Gear, &c.    ...						
Bedplate & Bearings						
	Totals					

N. B.—Copies of this four-page Schedule, printed large, on pages 16 inches by 10 inches size, can be had in quantity from the Publishers.

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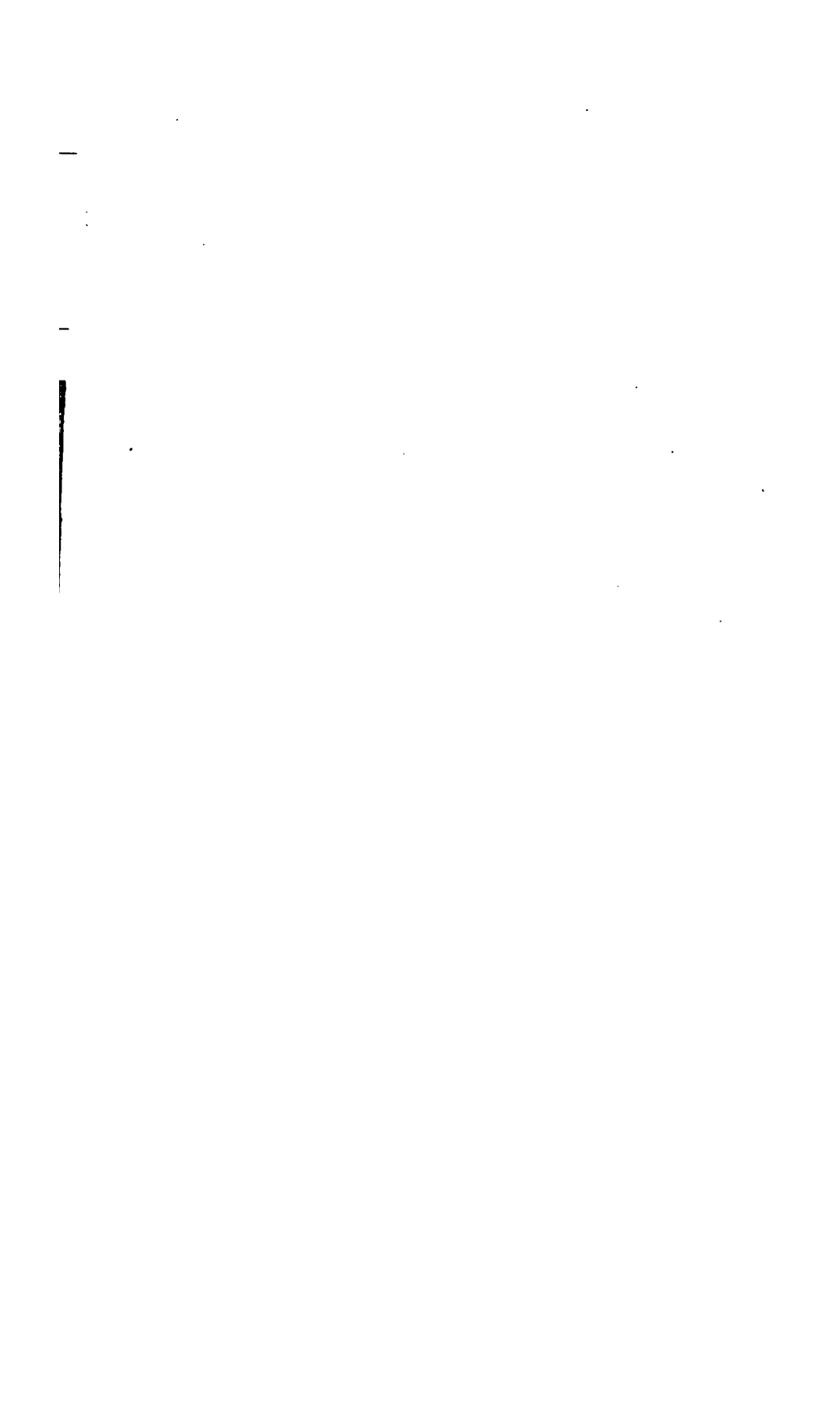
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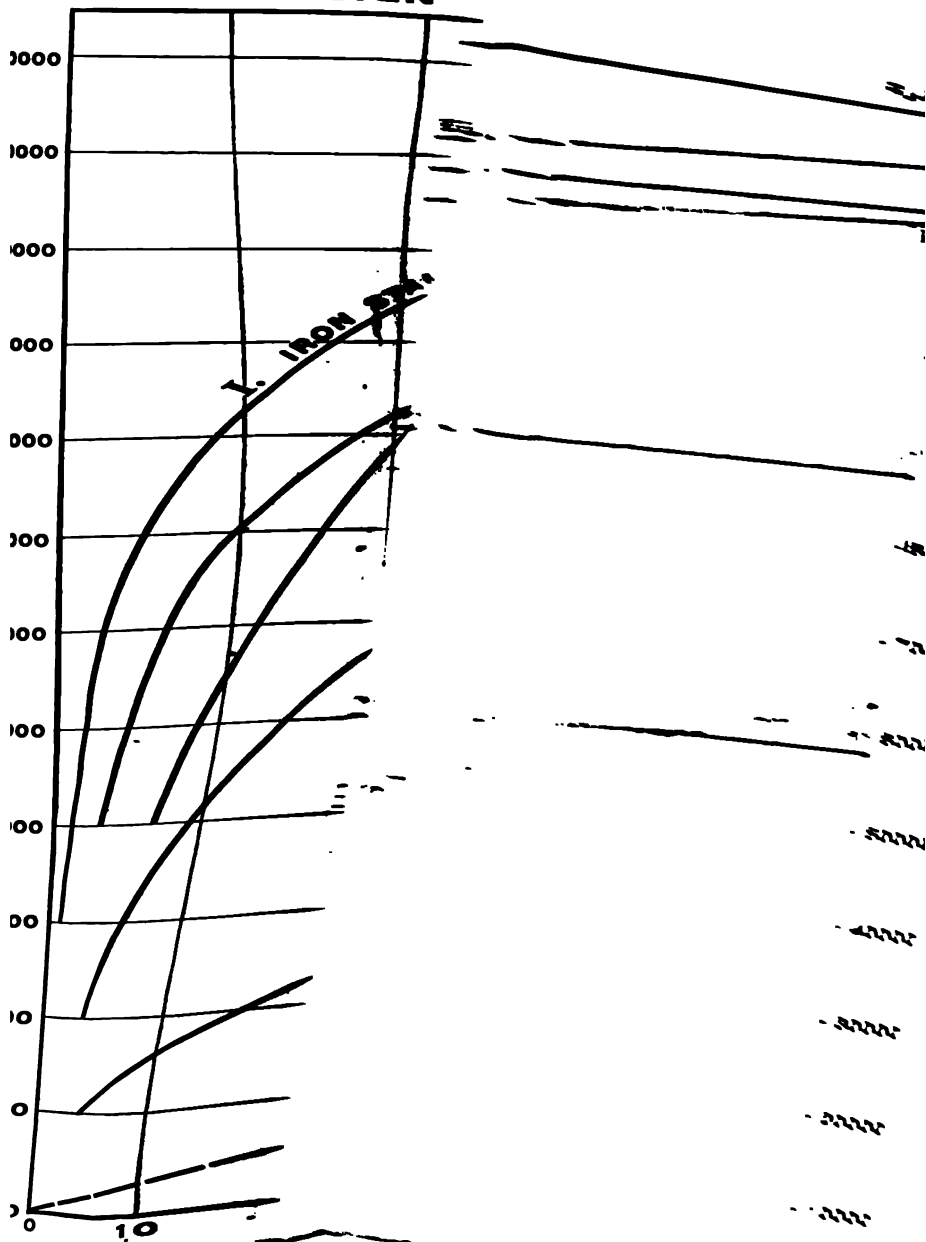
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# DYNAMO DESIGN



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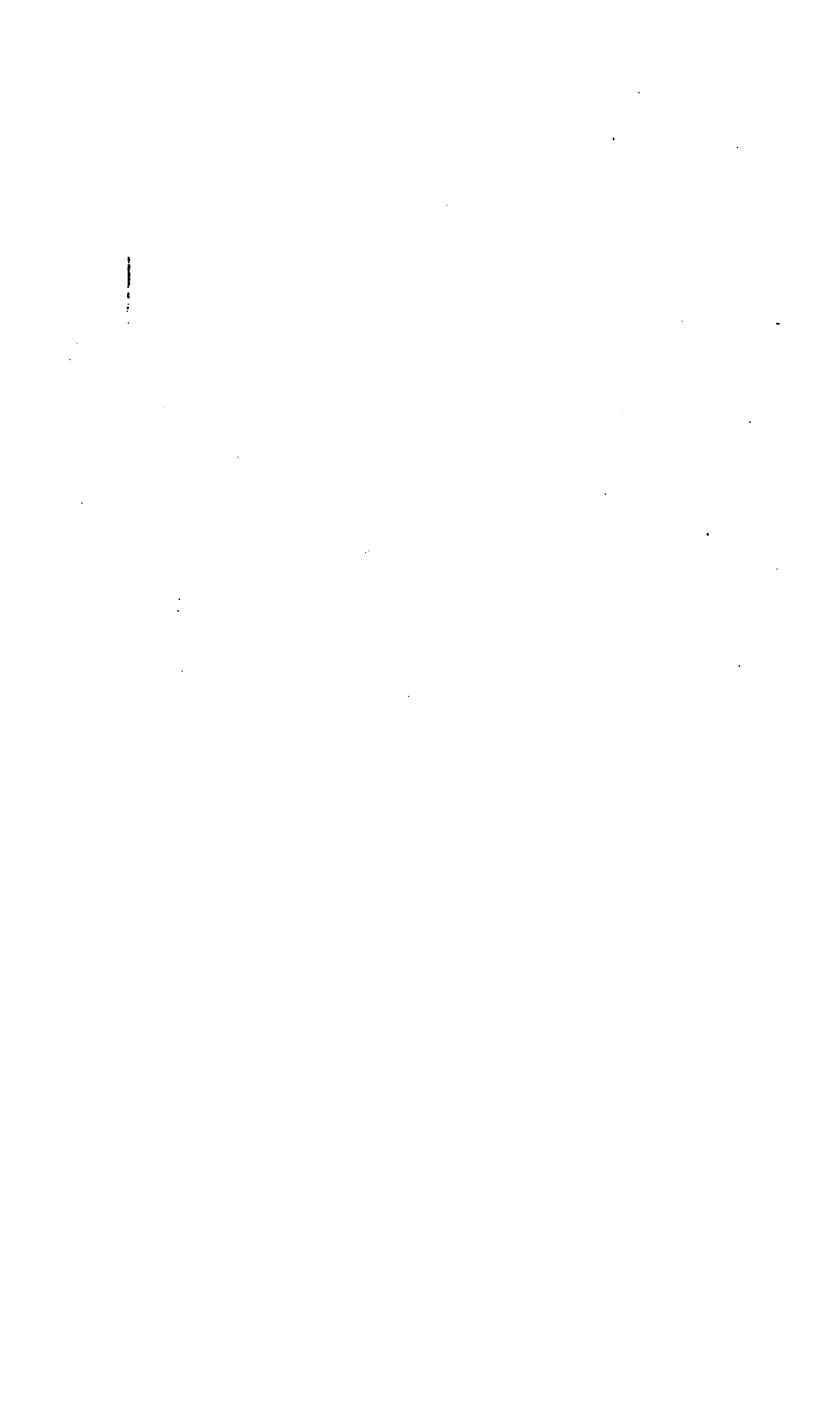
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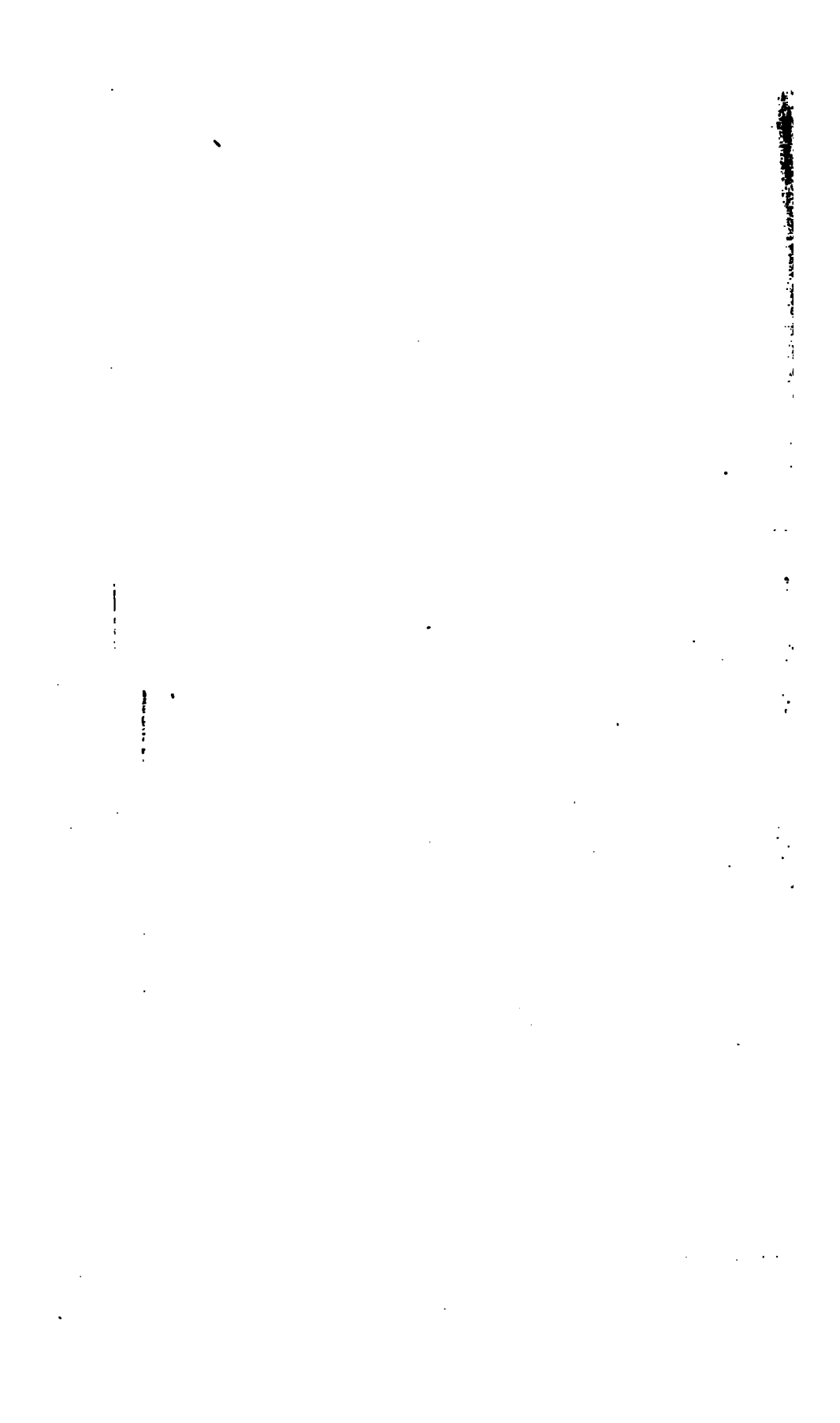
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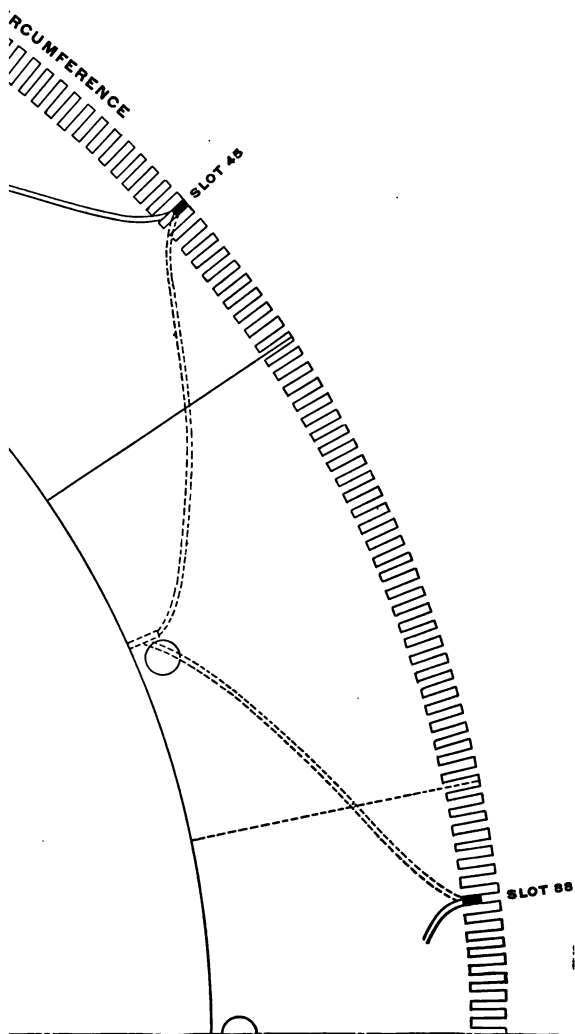
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1. *Staphylococcus aureus*

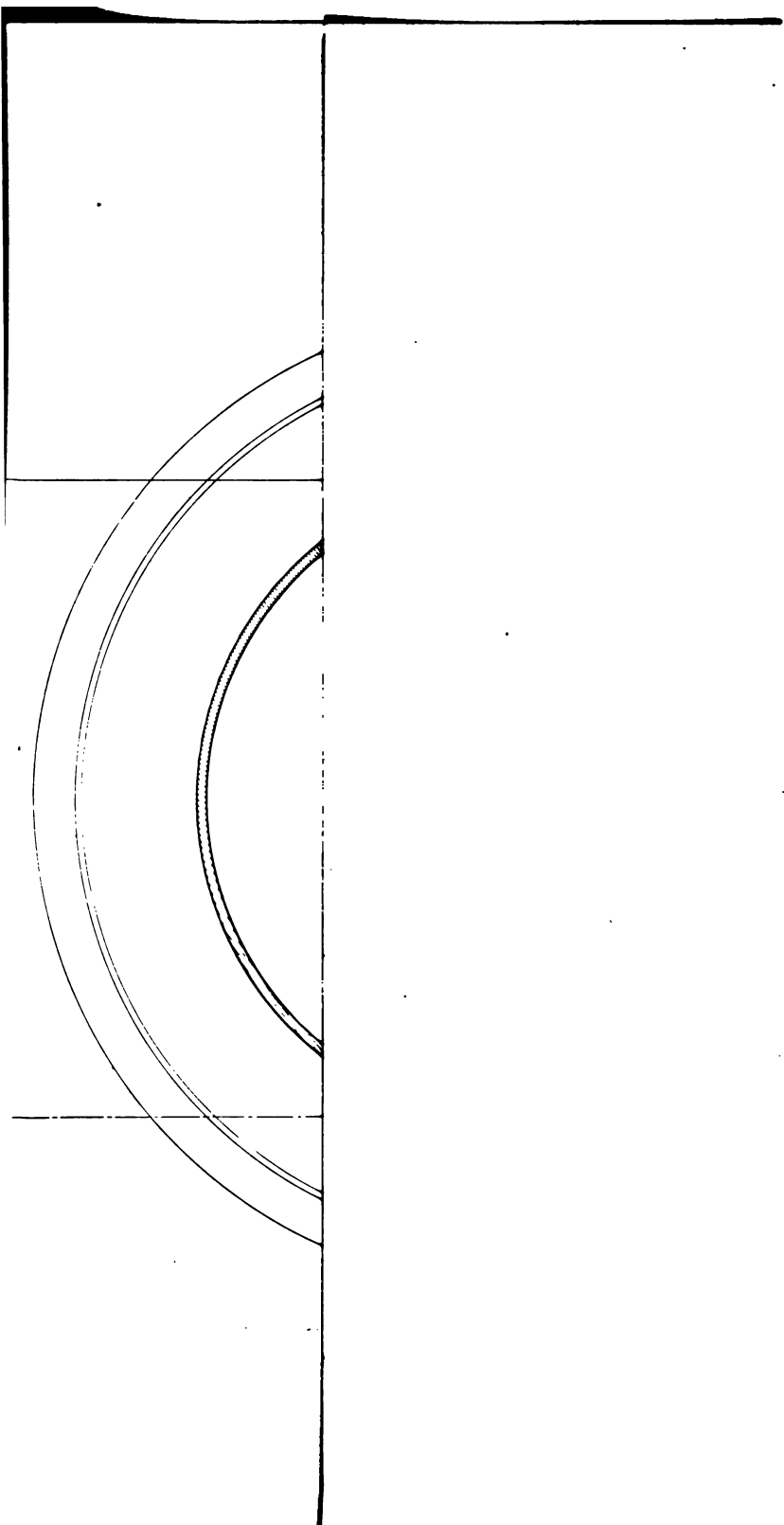
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PLATE VI



1. The first part of the document is a list of names and addresses of the members of the committee.

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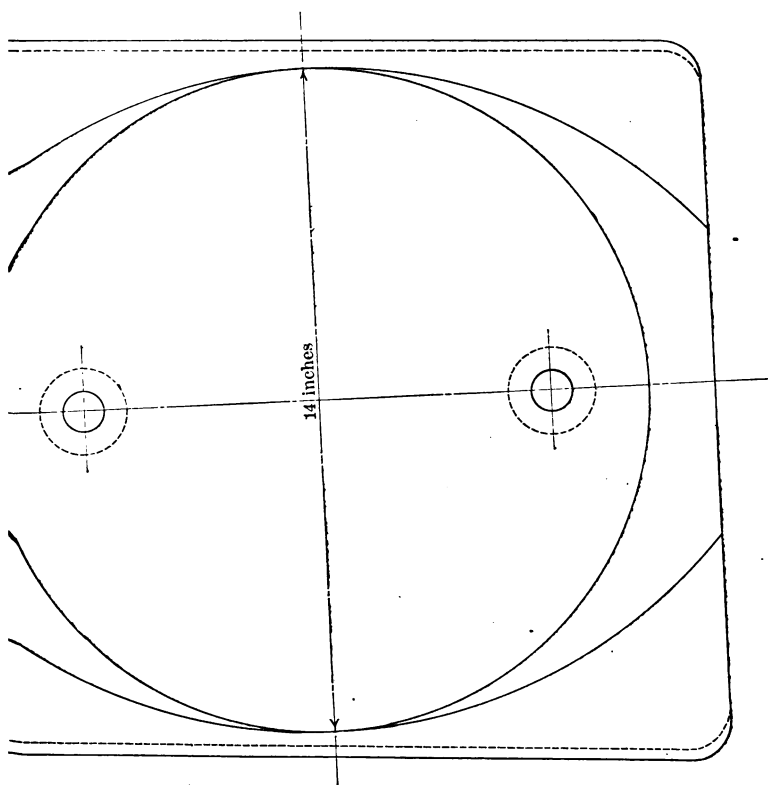


1. The first part of the document is a list of names and addresses of the members of the committee.

2. The second part of the document is a list of names and addresses of the members of the committee.

**DESIGN**

Scale 1:4



**POLE SHOE**  
Showing Skew form.

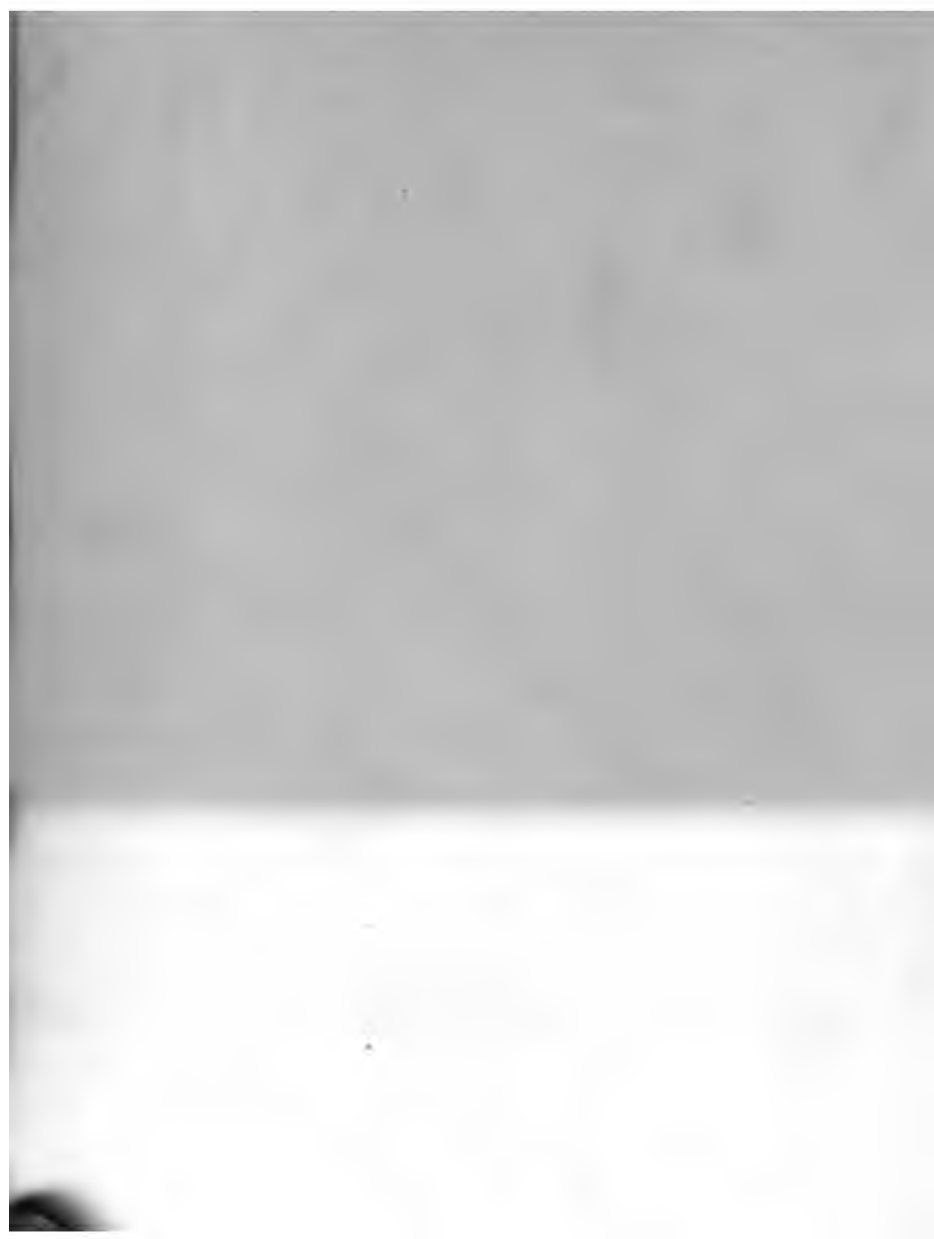






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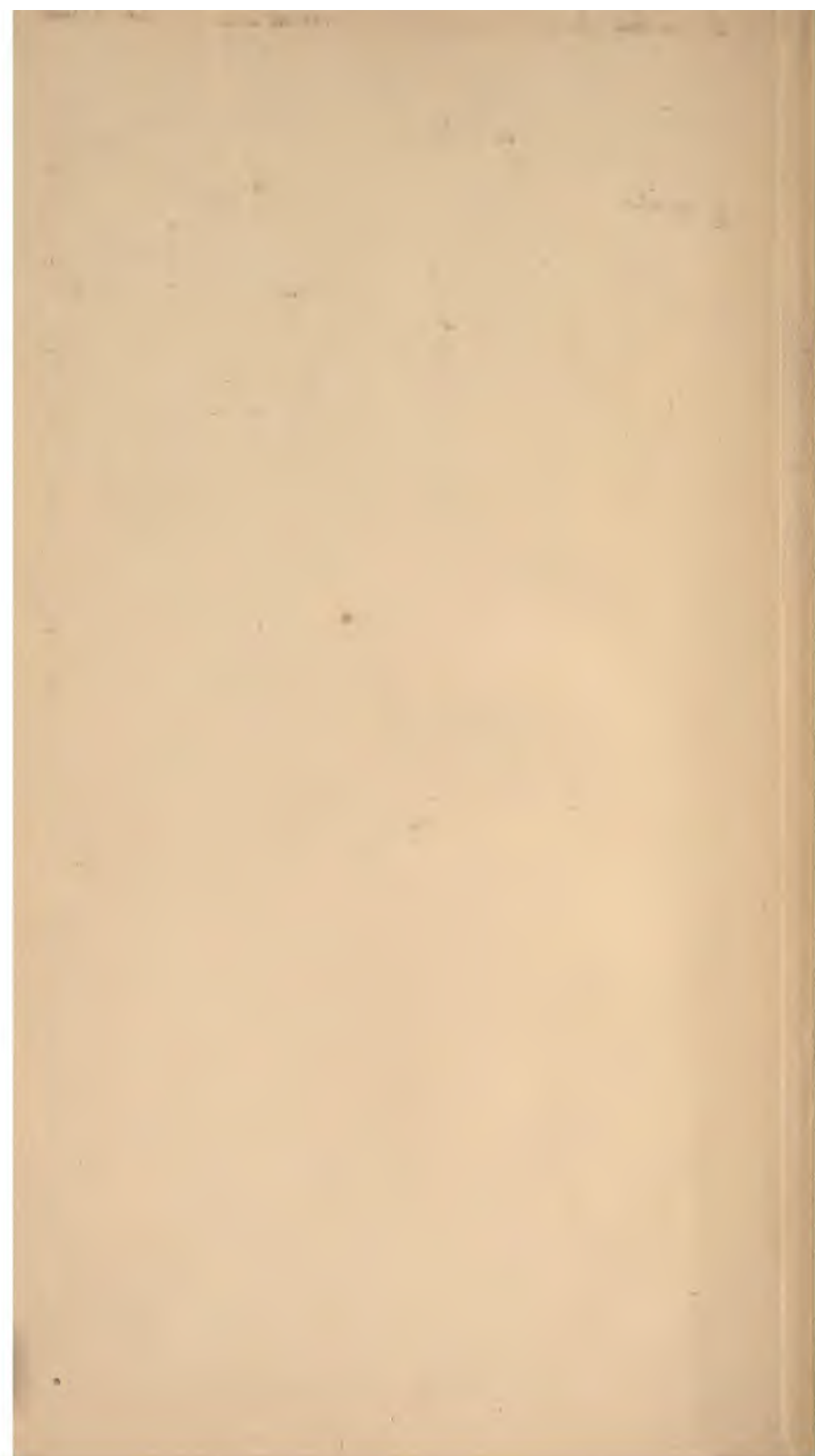












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